Enhanced CANDU 6®: Reactor Core Design and Safety Characteristics

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Abstract

The Enhanced CANDU 6® (EC6®) nuclear power plant is a mid-sized Pressurized Heavy Water Reactor design, based on the highly successful CANDU® 6 family of power plants, upgraded to meet today's Canadian and international safety requirements and to satisfy Generation III expectations. Atomic Energy of Canada Limited (AECL®) is completing the development and pre-project review of this design in readiness for new build projects this decade. The EC6 is based on natural uranium fuel, but is able to utilize additional fuel options, including the use of Recovered Uranium (RU or RepU) and Thorium based fuels. The EC6 offers the provenness of the CANDU 6 reference plant design, together with incremental enhancements that provide added benefits in defence-in-depth safety, operating margin, reliable performance and aging management.

This paper outlines the basis for CANDU core safety, based on generic reactor physics characteristics, and presents the specific EC6 enhancements to reactor core and physics design to ensure a robust safety case.

1. Introduction

AECL's Enhanced CANDU 6® (EC6®) nuclear power plant is the updated version of the well-established CANDU 6 family of units, meeting or exceeding Generation III expectations. The EC6 includes design upgrades to improve operability and reliability, and to assure a robust safety case [1]. By using incremental changes from the CANDU 6 Qinshan Reference Plant design, the EC6 maintains a high level of provenness, building on the excellent performance and well-known safety characteristics of the CANDU 6 design. The EC6 is designed to fully comply with the recently-updated Canadian regulations for nuclear power plants [2, 3], which represent international modern standards for reactor licensing and are consistent with IAEA and other international safety standards. This paper describes the main features of the EC6 core design and demonstrates how the overall EC6 design meets safety objectives for: Normal Operation, Anticipated Operational Occurrences (AOO), Design Basis Accidents (DBA) and Beyond Design Basis Accidents (BDBA).

1.1 Standard CANDU features

The EC6 core design closely follows the CANDU 6 reference plant core, retaining the standard CANDU-PHWR features such as: heavy-water coolant and moderator, simple fuel bundle design with natural uranium fuel in horizontal fuel channels, and on-power refueling.

The EC6 is equipped with control and safety systems designed to manage the reactor response to the range of reactor conditions, namely for normal operation, abnormal operating occurrences (AOO's), design basis accidents (DBA) and severe accident scenarios. They consist of a fully-computer-governed instrumentation and control system for the reactor core including regional flux and power control, load following and load cycling capability, and two full-capable reactor shutdown systems (shutoff rods, and liquid neutron absorber injection) separate from each other and from the reactor control system.

The reference plant CANDU 6 is the Qinshan Phase 3 two-unit design. It is the most recent one in a family of 11 CANDU 6 units operating in five countries around the world. The design of each successive CANDU 6 project has included incremental changes based on operational improvements, compliance with latest regulatory requirements, and incorporation of operating experience. These units have established an excellent operating and safety record. The lifetime in-service average capacity factor for the CANDU 6 fleet to 2009 is approximately 90%. These CANDU 6 units have performed consistently well for a range of jurisdictions and owner-operators. The fleet licensing basis is built on a consistent safety case, reviewed and approved individually by the national regulators in each of the countries of operation.

1.2 **Basis for EC6 Core Design**

The safety design basis for the EC6 overall is to update the reference plant design to:

- Meet or exceed Generation III nuclear power plant expectations,
- Comply fully with Canadian regulatory requirements from the Canadian Nuclear Safety Commission (CNSC),
- Retain the benefits of the proven existing CANDU 6 safety case,
- Ensure plant acceptability for an expanded seismic envelope,
- Further improve the robustness of the plant safety case.

In addition, the EC6 design basis includes: 60-year overall plant life, a targeted year-to-year capacity factor of greater than 94%, and a targeted lifetime capacity factor greater than 92% with standard interval of three years between maintenance outages.

While the general approach of the EC6 core design is to follow as close as possible the reference C6 design, some specific design changes are necessary in order to achieve the requirements and targets mandated in the EC6 design basis as described above. These EC6 core design improvements driven by the design basis are described later in Section 4.

2. Overall CANDU 6 Reactor Physics Characteristics

As with other reactor designs, the CANDU 6 design has established a balanced set of inherent reactor physics characteristics, combined with engineered safety systems, to comprise a comprehensive safety case. The EC6 design adapts the Reference Plant CANDU 6, as noted above, based on the same inherent characteristics, to further improve safety margins while improving plant operability and maintainability. The main characteristics of the CANDU 6 core, retained in EC6 design, are: small values of reactivity coefficients, relatively small changes in core conditions with time, low core excess reactivity, and long neutron lifetime.

2.1 Overall core configuration

The EC6 core consists of 380 horizontal pressure-tube type fuel channels. Each fuel channel contains 12 discrete fuel bundles, each 0.5 m long with 37 Zirconium alloy-clad fuel elements of natural UO_2.

CANDU reactor are refuelled routinely at power (about two channels per day), at a rate that compensates for the reactivity loss due to the depletion of U^{235} and the build-up of fission products in the core. Adjacent fuel channels are fed by coolant flow in opposite directions. Refuelling is bi-directional (fresh fuel for adjacent fuel channels is introduced from opposite ends of the reactor core), which has the benefit of preventing the development of flux tilts during operation. This is a continuous process throughout the reactor life that obviates the need to carry excess reactivity to compensate for fuel depletion, apart from some very small amounts (a few mk.) to compensate for “fuelling ahead” if a fuelling machine is planned to be taken out of service for maintenance. This core and refuelling layout ensures overall axial symmetry of neutronic properties due to both fuel and coolant, minimizing the required worth of local control absorbers. CANDU control devices are used mainly for routine power operation rather than reactivity compensation. The control devices, consisting of light-water zone compartments, adjuster rods (for flux shaping) and absorber rods (for rapid power reduction in anticipated operational occurrences, or AOOs), therefore have low total and individual reactivity worth. This is facilitated by the large core size, allowing for numerous control devices, well-distributed spatially in the moderator.

The total worth of all reactivity control devices in a CANDU 6 reactor is approximately 30 mk, with any individual device worth less than 2.5 mk. In this way it is impossible for the adverse movement of any individual device to lead to reactivity insertion greater than the total delayed neutron fraction, β, (5 to 5.5 mk under equilibrium conditions). Furthermore, the location of all reactivity devices in the low-temperature, low-pressure moderator (they do not penetrate the coolant pressure boundary) rules out the possibility of a control-rod ejection.

2.2 Power Manoeuvring

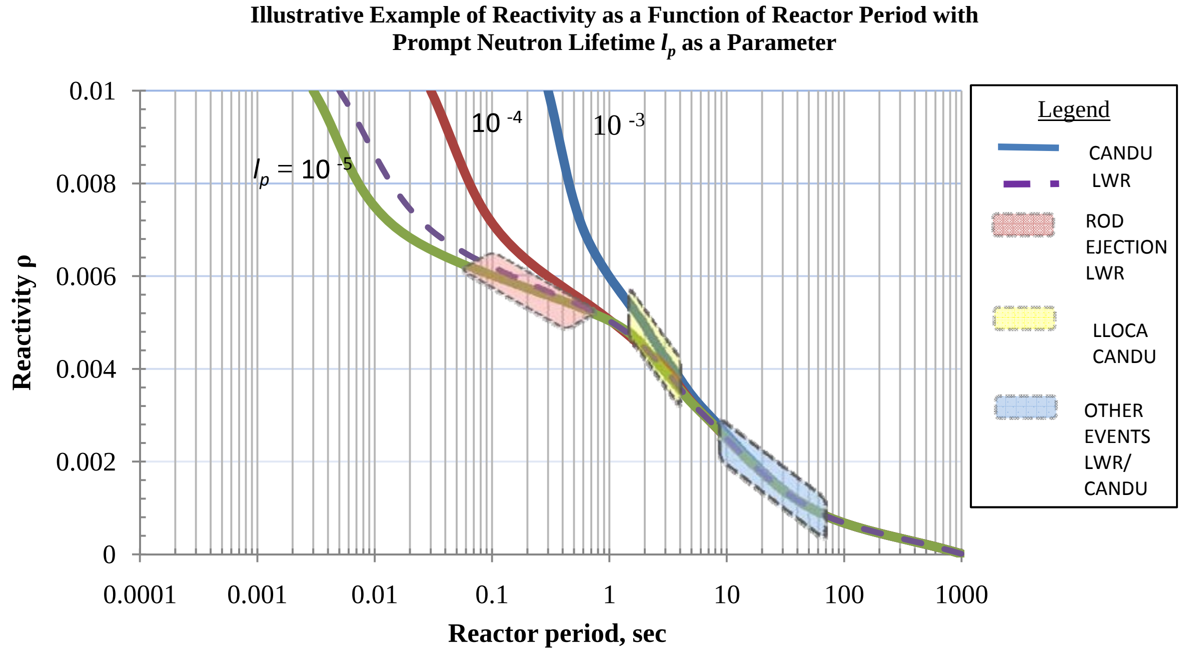
The EC6 core has very low values of reactivity coefficients. This means that the neutronic characteristics of the core do not change significantly as operating parameters vary little during normal reactor operation, such as moderator temperature or neutron poison concentration. In particular, the fuel temperature reactivity coefficient (FTC) is negative for the range of burnups in an operating core at nominal conditions. This provides an inherent negative fast feedback for any events which lead to increases in fuel temperature, such as a power rise, or accidents which interrupt fuel cooling. The overall power coefficient of reactivity (PCR) has a very low value, so that power manoeuvring from 0 to 100% full power requires very little adjustment of reactivity devices. This also simplifies shutdown management. The major reactivity change during power maneuvers or for a period of shutdown after normal operation, arises from Xenon-135 buildup and decay.

2.3 Rapid Changes in AOO’s or Accidents

Due to the use of heavy-water D_2O as moderator and to the separation of fuel in individual fuel channels, the EC6 core has a long neutron lifetime, in the order of 900 μs – about 30 to 45 times longer than that of typical PWR’s. The total delayed neutron fraction, β, decreases from the range 0.0073 for a fresh, unirradiated core, to the range of 0.0053 for an equilibrium core condition. For CANDU’s there is a unique contribution to β from photoneutrons (from gamma ray bombardment of deuterium in heavy water). As well as increasing β somewhat, these neutrons (including some with long half-life precursors) provide an inherent neutron source for startup after a lengthy shutdown.

The significance of the long neutron lifetime for EC6 is that, for hypothetical increases in reactivity near or beyond β, the reactor period (a measure of the length of time for reactor flux to increase by a factor e) does not decrease sharply as the reactivity increases. This means that CANDU reactors have an inherent degree of mitigation against sudden reactivity insertions. The reactor period for all conditions stays in a range where either of the two engineered shutdown systems (based on familiar and well-proven technology) readily terminate any reactivity transient before any prolonged overpower can occur.

Figure 1 shows the relationship between reactivity and reactor period for various values of prompt neutron lifetime, for the range of abnormal events and accident conditions. Typical values of reactivity changes during certain accidents classes for a PWR and a CANDU reactor are also indicated in Figure 2 under dashed lined areas with certain colour highlights. For ρ << β, the period for CANDU and PWRs for the same reactivity insertion is about the same. As ρ approaches β, the period for PWRs decreases sharply, whereas for CANDU it also decreases but fairly smoothly. For ρ > β, the period for PWRs is about 40 times smaller (i.e., faster) than for CANDU. This difference is important when comparing the relative safety and mitigation of each reactor type. The transition to a very fast power increase is sudden in the case of reactors cooled by light water, and much more gradual in CANDU design.



Ref. Neutron generation time data provided from S. Glasstone and A. Sesonske, 'Nuclear Reactor Engineering', Van Nostrand Reinhold, 1967.

Figure 1. Illustrative Example of Reactivity as a Function of Reactor Period with Prompt Neutron Lifetime as a Parameter

The long neutron lifetime in CANDU eliminates the possibility of events with reactor periods too short to control. The limiting reactivity insertion accident in CANDU is a large Loss-of-Coolant Accident

(LOCA) from a pipe break — a relatively unlikely event, and one which introduces a reactivity insertion of less than β, and does not result in prompt criticality; accordingly, the reactor period, and accompanying rate of flux change, are readily accommodated by either of the two shutdown systems acting alone.

3. Reactivity Coefficients

The safety importance of individual reactivity coefficients is a function of speed, size, and sign. As noted above, for CANDU reactors such as EC6, the reactivity coefficients lead to relatively small changes in core condition. The result is a reactor that has characteristics that do not change significantly over the operating range, that has relatively low speed of change due to the long neutron lifetime, and that has small absolute values of reactivity coefficients.

Fuel temperature coefficient (FTC) represents the fastest response to changes in fuel or coolant conditions with the timescale being set by slowing down of the fission products in the fuel just after fission. Its value is determined by the effect of temperature on absorption and production of neutrons in the fuel. As temperature increases, the energy level at which substantial absorption in U^{238} takes place (resonance region) broadens, resulting in increased neutron capture and decreased reactivity. However the opposite effect occurs in Pu^{239} – the increase in temperature moves more neutrons into a resonance region where the fission cross-section for Pu^{239} is increased. The contribution to the overall fuel temperature reactivity effect from U^{235} is relatively small. Hence, the net result is that the fuel temperature feedback coefficient in an operating CANDU is close to zero.

The nominal fuel temperature coefficient in EC6 has a small negative value (order of -1.5 µk/ºC) for a typical equilibrium core composition. For EC6, as for all CANDU reactors, the small fuel temperature coefficient plays almost no role in operation or safety – in particular, because of the long prompt neutron lifetime, there are no events which are so fast that the inherent negative feedback is required to mitigate them.

Coolant density coefficient of reactivity (also known as the coolant void coefficient) is generally a slower-acting coefficient than FTC. For CANDU core configurations, this is a positive coefficient. The effect of the coefficient is low, as a result of the coolant system configurations. Because the EC6 CANDU design has a subdivided, two-loop core, and because each loop has two separate inlet piping arrangements (one at each end), only one-quarter of the core fuel channels can experience rapid coolant voiding for the limiting event, large-break LOCA. This limits the maximum reactivity insertion possible to less than β, for the duration of this limiting scenario. It follows that for events where coolant density increases, such as overcooling events, the EC6 reactivity decreases moderately.

Moderator and coolant temperature coefficients of reactivity ─ In CANDU reactors, with a separate, low temperature moderator system with a very large volume, the possible rate of change of moderator temperature is very slow. Even if all moderator cooling is lost, the immediate heat up rate would be of the order 0.1ºC/second. Coupled with a reactivity coefficient of about 0.02 mk/ºC, this means that reactivity changes due to moderator temperature changes are small and slow-acting. The coolant temperature coefficient for CANDU cores is a separate effect, but is also small and of similar magnitude to the moderator temperature coefficient.

Power coefficient of reactivity (PCR) represents the combined effect of all individual coefficients as core conditions vary for a change in reactor power. Since all the individual coefficients are small, as noted above, the power coefficient is also small and is subject to only small magnitude variation. Because of this, the power coefficient in CANDU reactors is not a significant parameter affecting accident behaviour. With the long neutron lifetime inherent to the CANDU-6 design, either shutdown system, acting alone, responds to any accident condition to prevent excessive fuel overpower and maintain core temperatures within safety limits.

The small power coefficient and long neutron lifetime also contribute to a stable, readily controlled core. Stability analysis demonstrates ample control system margins for normal operations and the range of power manoeuvring.

4. EC6 design improvements

4.1 Design bases for licensing

AECL is proceeding with the pre-project regulatory review of the EC6 design by the Canadian regulator, the Canadian Nuclear Safety Commission (CNSC), based on comparison to the CNSC's technology-neutral reactor design guidelines. In Canadian practice, this type of review is intended to clarify the path to applying for a Construction License for a build project, when the formal, project-specific licensing process would occur.

The core design for the EC6 includes a set of adjustments to the reference plant CANDU 6 design, to ensure modern safety standards are met, with robust margins, meet expectations for plant operating reliability, retain proven design basis and features, and improve plant economics through modest output increase.

The safety case for EC6 core and neutronic design is based on the well-established safety characteristics of the CANDU-6 design, with demonstration of additional margins. This is in keeping with the overall EC6 target of meeting established safety goals with substantial margin. The EC6 generic target for Core Damage Frequency is <10-6/year, and the generic target for Large Release Frequency is <10-7/year. The EC6 core and neutronic design incorporates specific design changes driven by the following requirements, targets/ goals described in the design basis:

- Design for 60-year operational life, with pressure tube replacement at 30 years;
- Target of 92% lifetime average capacity factor ;
- Design capability for earthquakes at 0.3*g* level;
- Maintenance outages at standard 3 year interval, with a reference outage duration of 30 days;
- Large margins in safety case for design basis accidents;
- Ample reactor trip coverage to enable full-power, high capacity-factor operation throughout plant life.

4.2 EC6 core design features

The main core and neutronic design changes for EC6, which are incremental to the CANDU 6 Qinshan Reference Plant design, include the following:

Fuel Channels: Pressure tube thickness has been increased slightly, and manufacturing processes refined to minimize deformation during 30 year life duration (previous reference plant pressure tube design life was 25 years). Calandria tube thickness increased slightly, and calandria tube – end shield interface was improved to increase core protection for pressure tube failures.

Core Instrumentation: The Regional Overpower Protection (ROP) system instrumentation has been improved for Shutdown System #2 (SDS2) by adding further horizontal detector assemblies, improving coverage for some regions of the core. This allows increases in overall overpower trip setpoints, enabling greater operating margin with the same assurance of trip coverage.

Two fast neutronic trips are added in EC6 for each shutdown system, and the design incorporates improved digital control processing to reduce the time to activate shutdown.

Reactivity Control Mechanisms: EC6 incorporates two design refinements for the mechanisms of the control of reactivity. First, the array of adjuster rods (control absorbers used in power shaping and to enable load cycling) has been optimized to reduce the total reactivity worth of in-core rods, while keeping a balanced core flux and power distribution, and maintaining load-cycling capability. This reduction in the number of adjuster rods enables the EC6 to install additional absorber rods, normally positioned outside the core. The expanded system of absorber rods has sufficient negative reactivity to maintain the core in a guaranteed shutdown state with no requirement to place a large neutron poison concentration in the moderator. This greatly reduces the time to enter and exit from a major maintenance outage, and also reduces occupational dose and moderator cleanup burden.

Second, the design of individual reactivity control mechanisms has been improved by relocating the guide tube positioning springs outside the core. This improves spring robustness and also removes parasitic neutron-absorbing material from the core to improve fuel burnup.

Shutdown Systems: In addition to improving reactor trip instrumentation response (see above) the shutoff rods system (SDS 1) has been improved by optimizing the insertion spring strength and rod weight, to increase insertion speed, and by parking the rods, in poised position, following the contour of the calandria shell. These design modifications enhance the effectiveness of SDS1 by reducing the time for rod insertion after a trip signal.

5. EC6 core and neutronic characteristics

The EC6 Engineering Program has identified and specified design changes, including the major changes noted above, and confirmed the changes based on preliminary engineering and safety analysis. Licensing basis safety analysis and Probabilistic Safety Analysis (PSA) assessment is currently being completed for full-scale regulatory pre-project review later this year. Results show significant benefits in areas such as the following:

Fuel Channel Life: Taking account of the extensive CANDU operating record, the EC6 pressure tubes show substantial design margin to fitness-for-service guidelines for a 30-year operating life and 94% year-to-year capacity factor.

Fuel Channel Robustness: Assurance of calandria tube capability to survive a pressure tube failure offers a significant level of defense-in-depth for in-core accidents, and adds margin to achieve EC6 safety goal targets.

Reactivity Mechanisms: The optimized adjuster layout maintains load following capability while benefiting fuel burnup, balancing the impact of increasing fuel channel component thickness.

The expanded set of absorber rods greatly reduces the time taken to transition from full power operation to a full-maintenance ready shutdown state, from several days down to a few hours. Similar reductions in time are achieved in returning to power at the end of a maintenance shutdown. This contributes to meeting the 30-day standard outage design target.

The combination of reduced pressure tube deformation, improved coolant conditions and upgraded moderator purity, more complete core coverage by in-core monitoring instrumentation, and improved overpower trip processing leads to a greater operating margin between normal core flux/power distribution and local overpower trip levels, sufficient to assure full-power high-capacity operation throughout the entire plant life.

Shutdown Systems: Improvements to neutronic trip detection efficiency and processing speed, coupled with improvements to shut-off rod insertion speed, all mitigate the limiting design basis accident (large break LOCA) analysis results. As for other CANDU designs, either of the two shutdown systems would respond to a hypothetical "instantaneous" large pipe break, by shutting down the reactor within 1-2 seconds. For EC6, the design changes reduce the time period before shutdown, significantly reducing the reactivity transient, the power generated before shutdown, and reducing the resulting predictions of fuel and fuel channel temperatures, and increasing the margins to acceptance criteria.

The EC6 design maintains, and facilitates, the CANDU practice of demonstrating by tests during operating, the reliability of each shutdown system. The shutdown systems are each designed to achieve and demonstrate 10-3 demand unavailability. Coupled with the separate shutdown capability of the control system by itself, this means that the probability of an accident with failure to shutdown is two orders or magnitude lower than the overall core damage probability. Shutdown system failures are an extremely low contributor to plant probabilistic risk assessments.

6. Conclusions

The EC6 nuclear plant design is positioned to benefit from incremental design improvements supporting safety margins, licensing compliance, operating reliability and economics. The EC6 design process also ensures that design changes are incremental, and that the proven performance benefits and design basis from the CANDU 6 family of plants are retained.

The core design of the EC6 has followed this process, retaining the traditional elements of core hardware design, and core performance characteristics, while selecting changes to improve component robustness. These design changes improve safety margins, simplify and shorten maintenance outages.

The result is a well-balanced design where the combination of inherent characteristics and engineered systems provides for proven operating reliability and a well-supported safety case.

7. References

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