ACR FUEL DESIGN

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ABSTRACT

This paper summarizes the fuel design for the Advanced CANDU Reactor™ (ACR), the technology on which it is based, and the ACR fuel qualification program.

INTRODUCTION

The ACR offers a significant reduction in capital cost compared to current operating designs, and improvements in inherent safety characteristics and performance [1]. It is built on the traditional CANDU® fuel-channel design with on-power refuelling, and features light-water coolant, heavy-water moderator and reflector, enriched uranium CANFLEX fuel, and a reduced lattice pitch (distance between fuel channels). The core design retains important benefits of the well-established CANDU 6 reactor, and introduces additional improvements.

Fuel is not only at the heart of the ACR, it is a key enabling technology. By relaxing the requirement of being able to use natural uranium fuel, the reactor has been optimized to achieve other objectives, such as a significant reduction in capital cost. The design of the ACR fuel enables the use of light water as coolant, the reduction in lattice pitch, the elimination of three-quarters of the heavy water, and the achievement of negative void reactivity, which enhances the licensability of the reactor.

HIGH LEVEL REQUIREMENTS

Three high level requirements of the ACR fuel design are negative void reactivity, a burnup of ~21 MWd/kg (500 MWh/kg), and the use of existing, proven CANDU fuel technology. Coolant void reactivity in the ACR is negative under all applicable design and operating conditions, accounting for calculation bias and uncertainties. (Coolant void reactivity refers to the change in

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the reactivity of the core when the coolant is postulated to be completely removed; it does not correspond to a physical reactor state, since in a postulated loss of coolant accident (LOCA), it would take several seconds to discharge all the coolant from the core, and the 2 independent, fast-acting shutdown systems would intervene to shut the reactor down well before this happened. It is nonetheless a convenient calculational measure of the reactivity associated with a LOCA.) Coolant void reactivity in the ACR was made negative by increasing the contribution to slowing-down of the neutrons by the coolant, by significantly reducing the amount of heavy water in the moderator (reduced lattice pitch, and larger gap between the pressure tube and the calandria tube). Final "tuning" of the value of void reactivity was achieved by adding a small amount of neutron absorber to the centre element in the ACR fuel bundle [2].

The burnup selected for the ACR (21 MWd/kg) is sufficiently high to reduce fuel cycle costs (which are minimized at a higher burnup than in existing CANDU reactors), but low enough that sufficient CANDU fuel experience exists to maintain the excellent performance achieved with natural uranium fuel. The quantity of spent fuel will be reduced by about a factor of three compared to natural uranium fuel.

ACR fuel is based on three underlying CANDU fuel technologies: the CANFLEX 43-element fuel bundle [3], [4], the use of slightly enriched uranium (SEU) fuel to achieve extended burnup, and the use of the Low Void Reactivity Fuel (LVRF) concept to tailor void reactivity [5], [6]. AECL has extensive experience in these three underlying technologies [7].

MAIN FEATURES OF THE ACR FUEL DESIGN

The ACR fuel geometry uses the CANFLEX Mk 4, 43-element bundle qualified for CANDU 6 reactors with natural uranium fuel [3], [4]. The greater subdivision in the CANFLEX bundle (43-elements with two element sizes) reduces peak linear element ratings by 15 to 20% compared to a 37-element bundle operating at the same bundle power. The reduction in linear element ratings reduces peak centre-line temperatures and hence fission gas release, facilitating an increase in burnup. The first ring around the centre element has 7 elements, the second ring has 14 elements, and the third (outer) ring has 21 elements. The central element and the elements of the first ring have an outside diameter of 13.5 mm, and the rest of the 35 elements have an outside diameter of 11.5 mm. The CANFLEX bundle also incorporates critical heat flux (CHF) enhancing appendages that are attached to the sheaths at strategic locations at the ¼ and ¾ bundle axial planes to promote local flow turbulence and mixing of coolant between subchannels in the bundle. The shape and size of the buttons and their locations within the bundle have been optimized to increase CHF without significantly increasing bundle pressure drop [8]. The CANFLEX bundle is the latest evolution in CANDU fuel bundle design, and is ready for commercial implementation.

The outer 42 elements of the ACR fuel bundle contain SEU fuel pellets with 2.1 wt% U-235. The central element contains pellets of natural uranium blended with 7.5% dysprosium (a burnable neutron absorber). Dysprosium was chosen as the burnable neutron absorber because it is a fission product (albeit at lower concentrations), its reactivity behaviour with burnup matches the requirements for void reactivity reduction in the ACR, and there is sufficient irradiation experience to support its use in the ACR. The enrichment and poison levels were chosen to achieve the design requirements of ~21 MWd/kg burnup, and full-core void reactivity of about -7 mk.

While uniform enrichment has been chosen for the reference ACR fuel design, enrichment grading is an option for further reducing the peak linear element rating. A reduction of about 10% in peak linear element ratings in the ACR bundle could be achieved by using different enrichments in different rings of the bundle. This would increase operating and safety margins, at the expense of a slightly more complex bundle design. Enrichment grading is a standard feature of LWR fuel assembly design.

ACR fuel employs a proprietary internal element design that is optimized for extended burnup. The pellet shape (dish depth, chamfer angle and width, land-width), CANLUB thickness, and other features are based on both analysis, and irradiation experience in the NRU reactor at the Chalk River Laboratories. The internal element design provides internal volume to accommodate fission gas release lowering the fission gas pressure, and also minimizes inter-pellet sheath strains.

The endcap-to-sheath weld has been designed to avoid any sharp notches and associated stresses at the internal weld-upset region. The sheath thickness is thin to reduce neutron absorption, but was increased from the standard thickness in the CANFLEX Mk 4 design to prevent longitudinal ridge formation and axial collapse due to the higher coolant pressure and temperature in the ACR. The sheath collapses onto the pellets under coolant pressure and with pellet thermal expansion to promote good heat transfer, which lowers pellet centre-line temperatures and decreases fission-gas release compared to sheath that does not contact the pellet stack. At the same time, excessive sheath collapse (either axially or circumferentially) that could lead to higher strains and cracking is avoided.

The length of the fuel bundle (~500 mm) and the outside diameter are sized to operate in the pressure tube of initial internal diameter of 103.4 mm, and allows for a radial outward pressure tube creep of up to 4.5% during its 30-year life (before the reactor is retubed) operating above 90% capacity factor. As in current CANDU fuel, Zircaloy-4 is used for all structural components in the fuel bundle. The endplates, spacers, and CHF-enhancing buttons in the ACR fuel bundle are the same as in the CANFLEX Mk 4 bundle. Bearing pads are slightly higher, which further increases the CHF compared to the CANFLEX Mk 4 bundle.

Other small changes include a change in the endcap profile (which is square as in Bruce 37-element fuel rather than conical as in CANDU 6 fuel), and endplates at each end of the bundle that are flipped relative to one another to reduce initial element bow.

ACR FUEL QUALIFICATION

As in current CANDU fuel designs, ACR fuel must meet high-level requirements that arise from a number of reactor systems and operational considerations, including functional, reactor physics, heat transfer and transport, fuel channel system, fuel handling system, failed fuel detection and location systems, as well as safety and seismic considerations.

In addition, in order to ensure that fuel element failures do not occur in normal operation, that the fuel dimensions remain within operational tolerances, and that functional capabilities are not reduced below those assumed in safety analyses, design limits are being established called Specified Acceptable Fuel Design Limits (SAFDLs). This is an extension of the traditional approach used in CANDU fuel design and qualification that conforms to US and international practice.

The fuel qualification program will confirm that all configurations permitted by design tolerances in the fuel and in the reactor will maintain ACR fuel within the SAFDLs pertinent to safety during normal operations. This will be achieved via systematic assessments that include combinations as appropriate of tests, analyses, and engineering judgments. On-power and time/burnup-dependent changes will be considered, such as in material properties and in geometry. The assessments will be done for all credible damage scenarios organized into three specific groups as well as overall integrated tests, as follows:

Thermal Integrity. The objective of thermal assessments is to confirm that fuel sheath and pellets will not overheat. This will be achieved by confirming that fuel sheath will not dry out, that the pellet will not melt, and that in-reactor deformations (e.g., sag, droop) will not lead to any sheath or endcap contacting a neighboring sheath or pressure tube.

Structural Integrity of the Fuel Element and the Fuel Bundle. These assessments will confirm that critical components of the fuel bundle will not crack or break, nor will control be lost over the stability of the fuel bundle geometry. Specific assessments will include the following: static refuelling loads; refuelling impact; buckling; fatigue caused by lateral vibrations of the fuel element; fatigue caused by axial vibrations; cross-flow endurance; axial clearance between the fuel string and the channel; and secondary strains in the endplate.

Compatibility. These assessments will ensure that critical parts fit and that they have acceptable interactions with neighbors and other interfacing systems (e.g., geometrically, thermally, chemically, etc.). Specific assessments will include the following: fretting; sliding wear; bowing; dimensional compatibility with the fuel channel and with the fuel handling system; and crevice corrosion between the bearing pad and pressure tube.

Integrated Multiple-Effects. These refer to multiple-effects assessments such as irradiation tests and associated analyses. In addition to irradiations already performed on CANFLEX fuel, and extended burnup CANDU fuel irradiations, AECL is performing additional ACR-specific irradiation tests in the NRU reactor at the Chalk River Laboratories at high powers as well as to simulate bounding power ramps expected in the ACR.

Thus, testing will be augmented with analyses to show that design requirements are met for all permitted configurations. Analyses will consider all appropriate significant feedbacks and cumulative effects of related processes that cannot otherwise be tested. The main fuel performance code used in ACR fuel design is ELESTRES [9], although other supplementary codes may be used in support of verifying the acceptability of the ACR fuel design. The ACR fuel qualification program will be fully compliant with the ISO 9001 and CSA 286.7 quality assurance standards.

SUMMARY

ACR fuel is based on three well established, underlying CANDU fuel technologies: the CANFLEX fuel bundle geometry, extended burnup fuel, and LVRF. The reference ACR fuel design has 2.1% U-235 in the outer three rings of the CANFLEX bundle, with 7.5% Dy mixed with natural uranium in the centre element. This gives a burnup of ~21 MWd/kg, and negative void reactivity under all applicable design and operating conditions. These values may undergo slight changes as the fuel qualification program unfolds and as the design is further optimized.

The ACR fuel design will meet the set of high-level requirements traditionally used in CANDU fuel design, as well as additional Specified Acceptable Fuel Design Limits (SAFDLs), that will ensure that the fuel system is not damaged as a result of normal operation. The fuel qualification program will confirm that all configurations permitted by design tolerances in the fuel and in the reactor will maintain ACR fuel within the SAFDLs during normal operations. This will be achieved via systematic assessments that include combinations of tests, analyses, and engineering judgments. The assessments will be done for all credible damage scenarios organized into three specific groups as well as overall integrated tests: thermal integrity, structural integrity of the fuel element and of the fuel bundle, and compatibility of the fuel bundle with interfacing systems.

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