ENHANCED CANDU6: REACTOR CORE DESIGN AND FUEL CYCLE FLEXIBILITY

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Abstract

The Enhanced CANDU 6® (EC6®) is the updated version of the well established CANDU 6 family of units incorporating improved safety characteristics designed to meet or exceed Generation III nuclear power plant expectations. The EC6 retains the excellent neutron economy and fuel cycle flexibility that are inherent in the CANDU reactor design. The reference design is based on natural uranium fuel, but the EC6 is also able to utilize additional fuel options, including the use of Recovered Uranium (RU) and Thorium based fuels, without requiring major hardware upgrades to the existing control and safety systems. This paper outlines the major changes in the EC6 core design from the existing C6 design that significantly enhance the safety characteristics and operating efficiency of the reactor. The use of RU fuel as a transparent replacement fuel for the standard 37-el NU fuel, and several RU based advanced fuel designs that give significant improvements in fuel burnup and inherent safety characteristics are also discussed in the paper.

I. INTRODUCTION

AECL's Enhanced CANDU 6®[1] (EC6®) nuclear power plant is the updated version of the well established CANDU 6 family of units incorporating improved safety characteristics designed to meet or exceed Generation III nuclear power plant expectations. The EC6 is designed to fully comply with the recently-updated Canadian regulations for nuclear power plants [1, 2], which represent international modern standards for reactor licensing and are consistent with IAEA and other international safety standards.

The EC6 retains the excellent neutron economy and fuel cycle flexibility that are inherent in the CANDU reactor design. The reference design is based on natural uranium fuel, but the EC6 is also able to utilize additional fuel options, including the use of Recovered Uranium (RU) and Thorium based fuels, without requiring major hardware upgrades to the existing control and safety systems. This paper outlines the major changes in the EC6 core design from the existing C6 design that significantly enhance the safety characteristics and operating efficiency of the reactor. The use of RU fuel as a transparent replacement fuel for the standard 37-el NU fuel, and several RU based advanced fuel designs that give significant improvements in fuel burnup and inherent safety characteristics are also discussed in the following sections.

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II. STANDARD CANDU FEATURES

The reference design for the EC6 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. The EC6 core design closely follows this tradition by retaining the standard CANDU-PHWR features such as: heavy-water coolant and moderator, simple 37-el fuel bundle design with natural uranium fuel in horizontal fuel channels, and bi-directional on-power refueling.

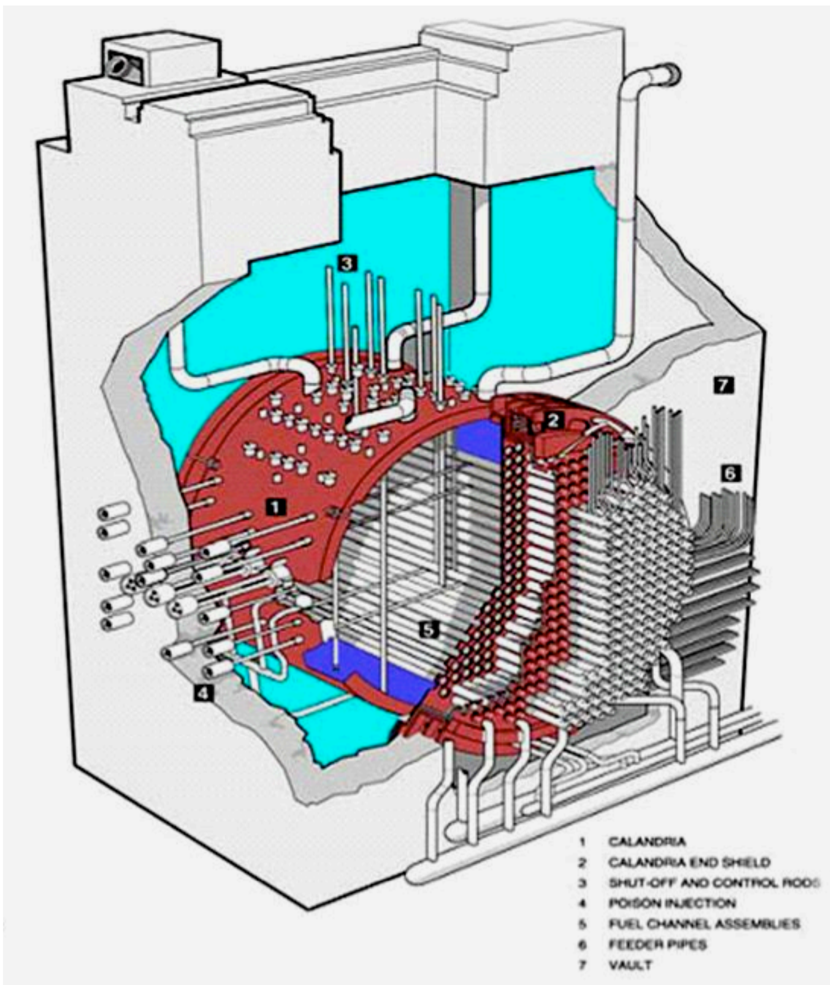

Figure 1: Typical CANDU 6 Reactor Assembly

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. The Reactor Regulating System (RRS), consisting of light-water zone compartments, adjuster rods (for flux shaping) and absorber rods (for rapid power reduction), is strategically deployed in the low-temperature, low-pressure moderator. There are two independent shutdown systems, each individually capable of shutting down the reactor for all design basis accidents. Shutdown System 1 (SDS1) consists of vertical spring-assisted gravity operated rods which fall into the moderator between the rows of fuel channels. Shutdown System 2 (SDS2) injects highly concentrated liquid neutron absorber into the moderator between fuel channels through horizontal perforated tubes under high pressure. Figure 1 shows the layout of the fuel channels, reactivity control and shutdown devices in a typical CANDU 6 reactor.

III. EC6 SPECIFIC CORE DESIGN CHANGES

The EC6 specific core design changes, which are incremental improvements 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 the 30-year design life (previous reference plant pressure tube design life was 25 years). Calandria tube thickness is also increased slightly, and calandria tube – end shield interface has been 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, especially the bottom half, of the core. This allows increases in overall overpower trip set-points, enabling greater operating margin with the same assurance of trip coverage.

The EC6 also incorporates two new neutronic trips for each shutdown system, and incorporates improved digital control processing to reduce the time to activate shutdown.

Reactivity Control Mechanisms: EC6 incorporates two design refinements for the reactivity control system.

First, the number of adjuster rods has been reduced from 21 in the current CANDU 6 to 11 in the EC6. The neutronic and mechanical designs of these adjuster rods have also been significantly simplified. All the adjuster rods in the EC6 are equal in length and consist of a single type of absorber. The layout of the reduced adjuster rod system has been optimized to reduce the total reactivity load, while achieving a sufficiently flattened core flux and power distribution, an adequate load-cycling capability, and ability to operate for more than 20 days without refuelling. The only significant compromise is the reduction of the xenon-override capability. However, this function, traditionally provided by the adjuster rod system in existing CANDU reactors, is no longer important in the current reactor operating environment. Several operating CANDU reactors, such as those in Darlington, have been operating successfully with a reduced adjuster rod system.

The reduction in the number of adjuster rods enables the EC6 to install additional absorber rods, normally positioned outside the core, in the vacant adjuster rod sites. The expanded system of absorber rods has sufficient negative reactivity to maintain the core in a guaranteed shutdown state (GSS) without requiring the addition of neutron poison in the moderator. This Rod-based GSS capability 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 removing the guide tube positioning springs from the bottom of the core. This modification removes parasitic neutron-absorbing material from the core to improve fuel burnup, and also eliminates the global top to bottom flux tilt due to these springs.

Shutdown Systems: In addition to improving reactor trip instrumentation response, 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 is initiated.

Four shut off rods (SORs) have been added to the four corner positions in the EC6 core to increase the number of SORs from 28 to 32. These four corner rods significantly increase the reactivity depth of SDS1 in accident scenarios where the two most effective rods (usually the corner rods) are assumed unavailable in the safety analyses.

Figure 2 shows the preliminary layout of the control and shutdown devices in the EC6 core. Up to ten new absorber rods can be deployed in the vacant adjuster rod sites. Detailed analyses are being conducted to determine the best strategy of allocating all or some of these extra absorber rods to SDS1, RRS, and GSS in order to meet their targeted performance requirements.

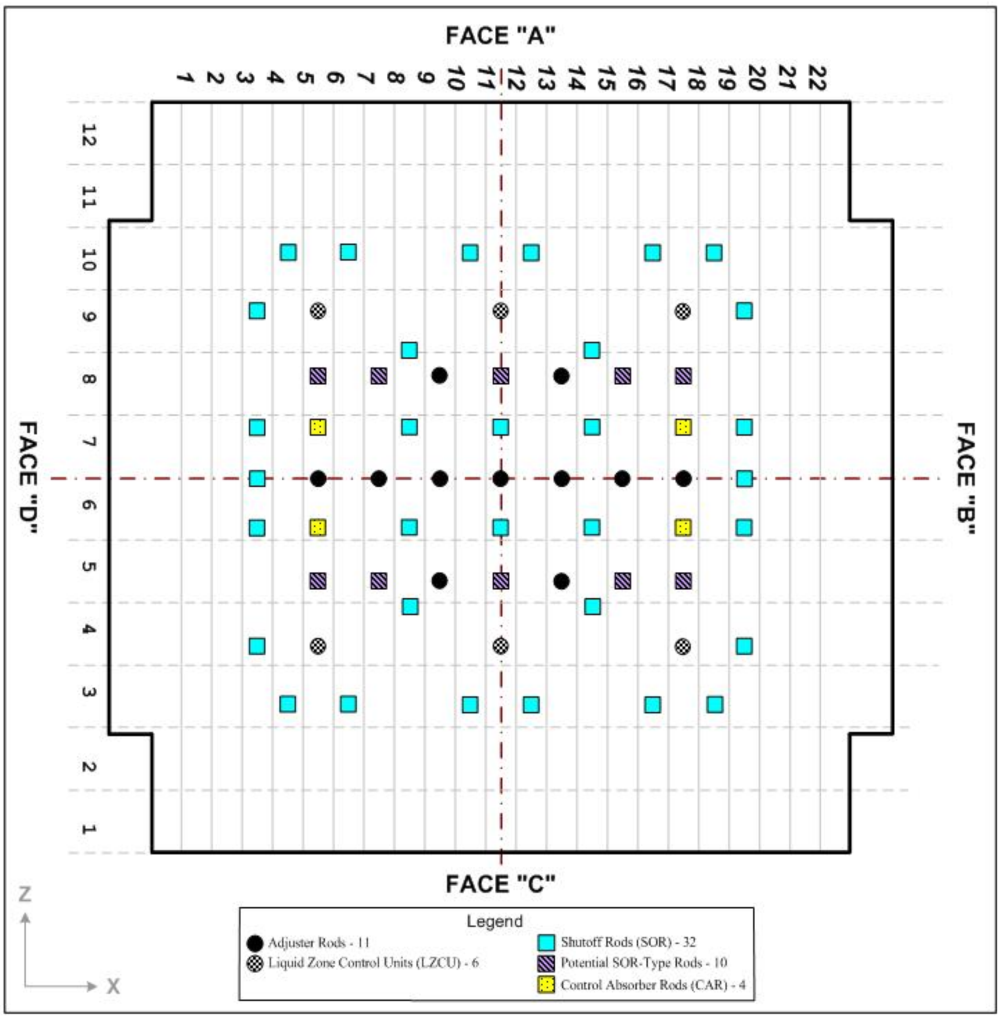

Figure 2: Preliminary Layout of Reactivity Devices in EC6

IV. EC6 FUEL CYCLE FLEXIBILITY

The EC6 retains the fuel cycle flexibility of CANDU reactors driven by a unique combination of high neutron economy, on-power fuelling, and simple fuel bundle design. Studies [3, 4, 5] have shown that

CANDU reactors can easily adapt to various advanced fuel cycles based on low enriched uranium, plutonium, thorium, and recovered uranium (RU) without requiring major hardware changes to the existing control and safety systems which have been optimized for the natural uranium (NU) fuel cycle. The ability to use RU without re-enrichment is a unique feature that differentiates CANDU reactors from other reactor designs.

IV.A Typical Isotopic Compositions of RU

The quantities of uranium isotopes present in the RU depend on a number of factors such as: the types of fuel used in different types of reactors, e.g. Advanced Gas-Cooled Reactor (AGR), Pressurized Water Reactor (PWR), and Boiling Water Reactors (BWR), the degree of initial ^{235}U enrichment, burnup of the discharged fuel, and the cooling period of the spent fuel. Most irradiated fuels are typically cooled for about five years to ensure that the highly active, i.e. short-lived, fission products have decayed sufficiently to permit fuel reprocessing without major radiological safety issues.

An extensive data base covering the detailed isotopic compositions of various RU produced by different companies in different countries can be found in a report issued by the International Atomic Energy Agency (IAEA) [6]. The current study of using RU fuel in CANDU reactors is based on the most common source of RU, which is the uranium recovered from the spent fuel of Light Water Reactors (LWR) with initial enrichment less than 5 wt% of ^{235}U. It can be seen in Table 1 that the bulk of the RU consists of four uranium isotopes, ^{234}U, ^{235}U, ^{236}U and ^{238}U. As expected, ^{238}U accounts for over 98% of the RU. ^{235}U can vary from as low as 0.6 wt% to slightly over 1.0 wt%. ^{234}U content varies between 0.02 to 0.03 wt%, and ^{236}U content between 0.5 to 0.6 wt% . The other uranium isotopes are often ignored in reactor physics simulations because their quantities are too small to have any significant influence on the neutronic properties of the RU fuel. However, some isotopes, ^{232}U in particular, can present significant radiation hazards even at extremely low level. Therefore, all uranium isotopes and even trace-quantities of impurities are important considerations in the assessment of RU fuel handling and processing.

Table 1: Isotopic Composition of Uranium in Spent LWR Fuel after 5 Years Cooling

Uranium Isotope	Burnup 40 MWd/kg Initial Enrichment 4.0% ^{235}U	Burnup 48 MWd/kg Initial Enrichment 4.0% ^{235}U	Burnup 48 MWd/kg Initial Enrichment 4.5% ^{235}U	Burnup 60 MWd/kg Initial Enrichment 4.1% ^{235}U
	Grams	Grams	Grams	Grams
^{232}U	1.71E-03	2.78E-03	2.86E-03	4.28E-03
^{233}U	2.90E-03	3.28E-03	3.81E-03	3.54E-03
^{234}U	2.11E+02	1.83E+02	2.19E+02	1.63E+02
^{235}U	1.00E+04	7.73E+03	1.03E+04	4.92E+03
^{236}U	4.96E+03	5.29E+03	5.83E+03	5.68E+03
^{237}U	3.48E-05	4.40E-05	4.38E-05	4.99E-05
^{238}U	9.33E+05	9.24E+05	9.21E+05	9.13E+05

Note: Table reproduced from reference 6; basis of data is with respect to 1 tonne of initial heavy atoms

IV.B Compositions of RU used in EC6 Study

The current study is focused only on the reactor physics aspects of using RU in the EC6. Therefore, only the four most important uranium isotopes, ^{234}U, ^{235}U, ^{236}U and ^{238}U are explicitly represented in the reactor physics models. Traces of impurities in the RU fuel are also ignored. These simplifications should have little impact on the conclusions of this study because the small fluctuations of the uranium isotopic contents between different batches of the manufactured RU would have a much bigger influence on the RU neutronic properties.

All RU calculations in this study are based on the specifications from a typical RU supplier. Constant concentrations of 0.025 wt% ^{234}U and 0.40 wt% ^{236}U are assumed in all the RU fuels. The ^{235}U content is a variable which is adjusted to meet specific fuel burnup targets. The remaining RU component is ^{238}U. Lattice physics calculations were performed using WIMS-AECL version 3.1 with the ENDF/B-VII data library [7]. Full-core reactor simulations were performed using RFSP version 3.5 [8].

IV.C Summary of RU Fuel Cycle Study for EC6

The two most important goals in the EC6 RU study are:
- Development of a NU equivalent fuel (NUe) that can be used as a transparent replacement of the standard NU 37-el fuel in EC6 and in existing CANDU reactors, and
- Development of a RU fuel design that can achieve a burnup up to 14 MWd/kgU, i.e. about twice the current NU burnup, using the Canflex (43-el) fuel bundle design

Figure 3 shows the configurations of the fuel elements in the standard 37-el fuel bundle and Canflex fuel bundle designs. Canflex fuel bundle design is the preferred design for high burnup fuel cycles in CANDU reactors because it achieves a reduction of up to 20% in the linear fuel element rating from that in a standard 37-el bundle design for the same bundle power. Lower fuel element rating reduces the risk of fuel failure at high burnup.

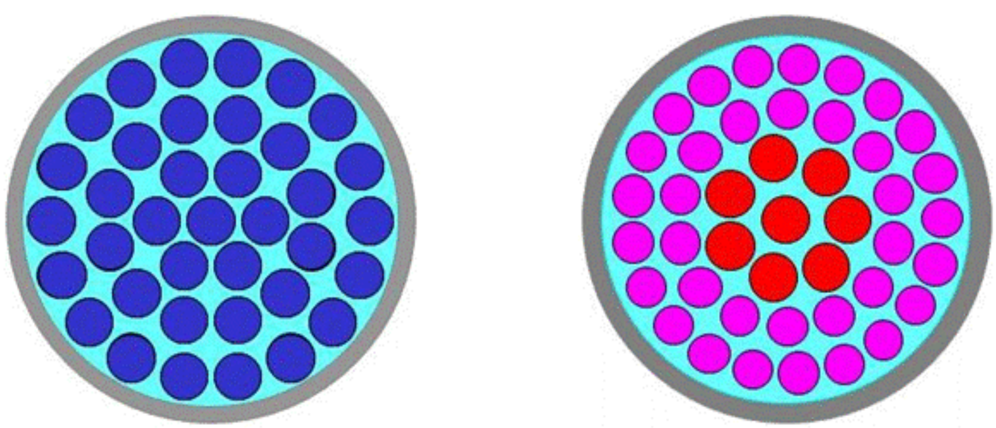

Figure 3: Configurations of Standard 37-el (left) and Canflex (right) Fuel Bundle Designs

The reduction in fuel element rating in the Canflex design from the standard 37-el design is achieved by two design changes:
- An increase in the number of fuel elements from 37 to 43, and

- A flattened power distribution across the bundle by making the inner 8 elements slightly larger than the outer 35 elements

Scoping calculations using WIMS-AECL showed that uniform RU fuel with 0.728 wt% ^{235}U using the standard 37-el fuel bundle design is almost a perfect match of the standard NU 37-el fuel. Also, an average discharge fuel burnup of about 14 MWd/kgU can be achieved by using RU with 0.95 wt% ^{235}U in all the fuel pins of a Canflex fuel bundle. These observations are illustrated in Figure 4, which shows the lattice k-infinities of NU, NUe, and high burnup RU fuels in the EC6.

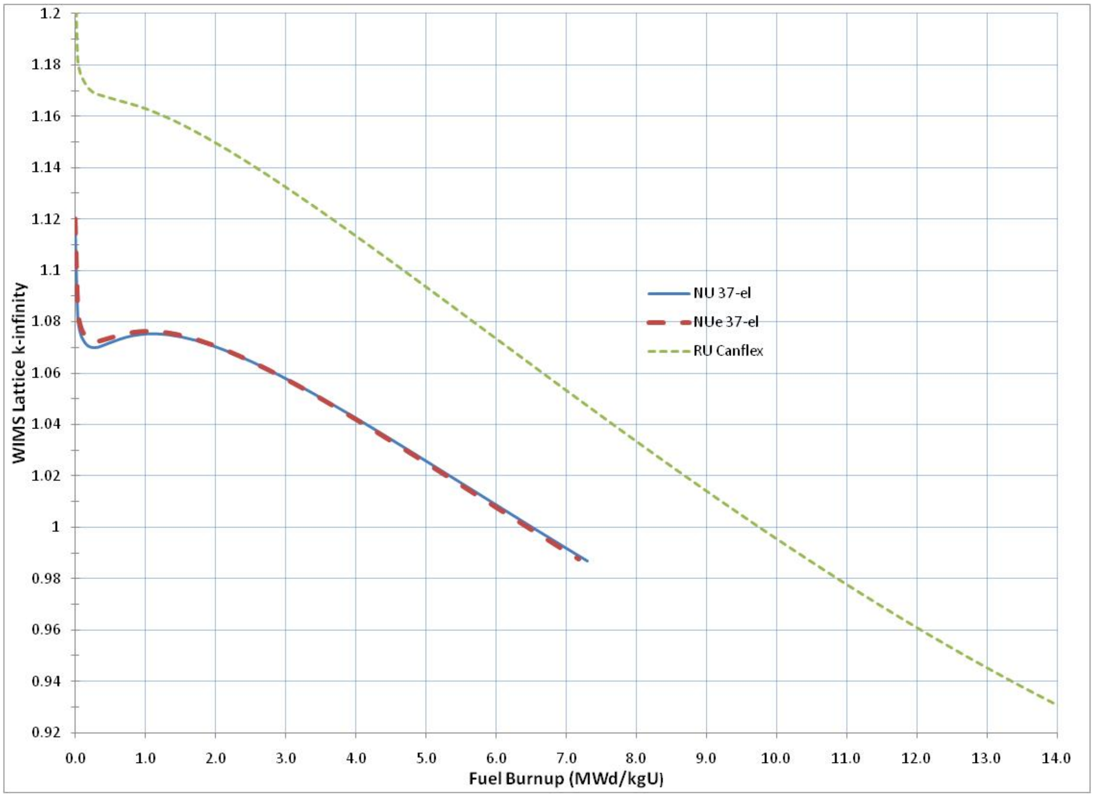

Figure 4: Lattice k-infinity of NU, NUe and RU Fuel in EC6

Table 2 gives a summary of the preliminary results of using NUe fuel and high burnup RU fuel in the EC6. Corresponding results for the standard NU fuel cycle are also shown for comparison purposes. It can be seen that the NU results and NUe results are almost identical in terms of channel power, bundle power, linear element ratings, discharge fuel burnup, fuelling scheme, and radial power form factors. Other neutronic parameters, such as coolant void reactivity (CVR), fuel temperature coefficient (FTC), and delayed neutron parameters are also very similar. The ^{235}U content in the NUe is 0.728 wt%, which is marginally above the value of 0.711 wt% in NU in order to account for the parasitic absorptions in ^{234}U and ^{236}U. The ability of CANDU reactors in general and the EC6 in particular, to use RU without requiring re-enrichment, is a powerful demonstration of the excellent neutron economy inherent in the CANDU reactor design.

The NUe fuel cycle offers both economic and environmental incentives to new EC6 customers as well as current CANDU owners using NU fuel. The fuelling cost of a NUe CANDU is expected to be lower than that of a NU CANDU because the cost of the NUe fuel is expected to be lower than NU fuel. The NUe fuel is expected to be manufactured by down-blending raw RU from spent LWR fuel with depleted uranium fuel (DU) from fuel enrichment plants. Both raw RU and DU are currently considered as waste products not useful in LWR applications unless they are substantially re-enriched. Hence, the NUe fuel cycle in CANDU reactors is an environmentally friendly concept by encouraging the re-use and recycle of nuclear materials in a simple and practical way. The transition from NU to NUe in existing CANDU reactors is expected to be essentially transparent to the operators in both operating and licensing procedures.

Table 2: Summary of NU and RU Fuel Cycle Characteristics in EC6
(Based on preliminary results for comparison purposes only)

Initial U isotopes (wt%)	NU (37-el bundle)	NUe (37-el bundle)	RU (Canflex 43-el)
^{234}U	0.005	0.025	0.025
^{235}U	0.711	0.728	0.950
^{236}U	0.0	0.400	0.400
^{238}U	99.284	98.847	98.625
Core-Average Discharge Burnup (MWd/kg)	7.2	7.2	14.4
Maximum Time-Average Channel Power (kW)	6559	6543	6520
Maximum Time-Average Bundle Power (kW)	805	806	774
Maximum Instantaneous Channel Power (kW)	6923	6920	6862
Maximum Instantaneous Bundle Power (kW)	834	834	828
Maximum Instantaneous Element Rating (kW/m)	54	54	43
Fuelling Scheme (bundle/shift)	8	8	4

Table 2 shows that the core-averaged discharge fuel burnup of the high burnup Canflex RU fuel is 14.4 MWd/kgU, i.e. twice that of NU and NUe fuels. The doubling of fuel burnup is achieved by a modest increase in the ^{235}U content from 0.711 wt% in NU to 0.950 wt% in RU. The cost of RU with 0.95 wt% ^{235}U is expected to be significantly lower than the equivalent low enrichment uranium (LEU) fuel, thus further improving the economic advantage of using RU in CANDU reactors.

The reactivity of the high burnup RU fuel, as shown in Figure 4, is significantly higher than that for the NU and NUe fuels. The refuelling power ripple in the high burnup RU core is brought down to a level comparable to that in the NU , or NUe core by changing the fuelling scheme from 8-bundle-shift for NU fuel to 4-bundle-shift for high burnup RU fuel. There is no increase in the overall fuelling machine duty because the core-averaged discharge fuel burnup has been doubled. This modification in fuelling scheme also slightly reduces the maximum channel power and maximum bundle power from the NU values. As expected, the maximum linear element rating is reduced by 20% because of the use of the Canflex fuel bundle design. The reduced linear element rating facilitates high burnup by reducing the risk of potential fuel failure. Detailed analyses designed to further assess the potential impact of using high burnup RU fuel on the reactor control and safety systems are being conducted for the EC6.

IV.D Potential use of RU to Customize Reactivity Coefficients in EC6

The EC6 is designed for the international market with diverse safety and licensing requirements. There might be advantages, especially to enhance marketing prospects in certain jurisdictions, to custom-tailor the reactivity coefficients of the EC6 in order to satisfy customer expectations. The end-product is an optimization of the reactivity coefficients, such as CVR, FTC, PCR (power coefficient of reactivity), fuel burnup, and ^{235}U content in the RU fuel, according to the requirements of a specific customer. The versatility of the CANDU design with inherent high neutron economy offers a wide range of possibilities using the RU fuel cycle.

A large number of scoping physics calculations has been performed to identify potentially promising RU fuel designs that can be used to custom-tailor reactivity coefficients, fuel burnup, and ^{235}U content in the RU fuel. The standard 37-el fuel bundle design is used for fuel burnup in the range between 7.0 and 8.0 MWd/kgU, which is well within the fuel burnup range in current CANDU reactors. The main features of these fuel bundle designs include;

- ^{235}U content between 0.85 wt% and 0.95 wt% in RU in the outer 36 pins
- Central pin is a custom-tailored neutron absorber such as
    - Mixtures of depleted uranium and dysprosium oxides
    - Dysprosium oxides in zirconium oxide matrix
    - A simple neutron absorber such as a stainless steel rod

Significant reductions in CVR and FTC, and an increase in fuel burnup if desired, are within the possibilities of this design. It is potentially possible to achieve a slightly negative overall PCR, if this is required.

The Canflex fuel bundle design is used for fuel burnup in the range between 10 and 14 MWd/kgU. The ^{235}U content is chosen to be 0.95 wt% in the outer 42 pins. The central pin is a custom-tailored neutron absorber as mentioned above. The overall fuel design is flexible enough to deliver an optimized solution between reactivity coefficients and fuel burnup to meet specific customer requirements.

V. CONCLUSIONS AND SUMMARY

The EC6 nuclear plant design benefits 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 EC6 retains the traditional fuel cycle flexibility of CANDU reactors, including the capability of using RU without the need for re-enrichment. Preliminary results demonstrated the feasibility of two important RU fuel applications in the EC6: a) NUe fuel that is a transparent replacement of the standard NU 37-el fuel, and b) RU fuel in Canflex bundles that can achieve twice the discharge burnup of standard NU fuel.

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