CANDU Advanced Fuels and Fuel Cycles

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Abstract

CANDU[©] natural uranium fuel is an outstanding product that is simple in its design and manufacture, low cost, extremely neutron efficient, and excellent in its performance. Nonetheless, advanced CANDU fuels and fuel cycles offer many benefits. The CANFLEX[©] fuel bundle with natural uranium fuel reduces peak linear element ratings and improves thermalhydraulic performance, enhancing operating and safety margins. When CANFLEX is used as the carrier for slightly enriched uranium (SEU) fuel, operating margins are even further improved, uranium utilization is increased, and fuel cycle costs and the quantity of spent fuel per unit energy are lowered. Uranium recycled from the reprocessing of spent LWR fuel may be a particularly attractive source of enrichment, as it can be used as-is in CANDU, without re-enrichment. The CANDU reactor offers several options for the use of MOX fuel with plutonium recycled from spent LWR fuel, which again extends uranium utilization, and reduces the spent fuel burden. Alternatively, the high neutron economy of the CANDU reactor, and the simple fuel bundle design, can be exploited in advanced recycle options such as DUPIC (Direct Use of Spent PWR and BWR Fuel In CANDU), that offer advantages over conventional reprocessing in cost, process complexity, and/or environmental impact. Plutonium from dismantled nuclear weapons can be utilized as CANDU MOX fuel in an effective disposition option that would contribute to world peace and disarmament. While thorium fuel cycles offer a long-term source of fissile material as well as synergism with breeder reactors, there are near-term thorium fuel strategies that can be utilized in the CANDU reactor.

This paper highlights recent developments in advanced CANDU fuels and fuel cycles.

Keywords: CANDU, advanced fuel cycles, CANFLEX, DUPIC, SEU, MOX, thorium, Parallex, plutonium disposition

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1. Introduction

Fuel is the heart of a nuclear reactor. CANDU fuel is characterized by a number of features. A CANDU fuel bundle is small, lightweight, simple in its design and manufacture, and consists of only 7 components: ceramic pellets, sheath, CANLUB coating applied to the inside of the sheath, end-caps, bearing pads, spacer pads, and end-plates (the CANFLEX bundle also has CHF-enhancement buttons). This simplicity facilitates localization of fuel manufacturing (all countries having CANDU reactors also have CANDU fuel fabrication facilities). It also simplifies the manufacture (and introduction) of advanced fuels, whether SEU, MOX, DUPIC, thoria, or other advanced fuels requiring remote fabrication. The performance of CANDU fuel continues to be excellent. The current rate of confirmed fuel defects in Canadian CANDU reactors is extremely low, approaching 2 defects per million fuel elements [1]. The requirement of being able to use natural uranium in the CANDU reactor has resulted in a reactor and fuel design having excellent neutron economy, and consequently, high uranium utilization. This high neutron economy also applies to advanced fuel cycles, and the uranium utilization for any particular fuel (SEU, MOX) is nearly 50% better in CANDU than in an LWR.

2. CANFLEX

CANFLEX is a 43-element bundle, in which the inner 8 elements (a central element surrounded by the inner ring of 7 elements) each have a slightly larger diameter than the outer 35 elements (arranged in 2 rings of 14 and 21 elements). The greater number of elements, and the two element sizes reduce peak linear element ratings by about 20% compared to a 37-element bundle, for the same bundle power. The lower fuel temperatures, and thus lower fission gas gap inventories, result in improved operating and safety margins. In addition, the use of two planes of non-load-bearing heat-transfer enhancement buttons in the CANFLEX design improves the critical heat flux (CHF) and critical channel power (CCP).

The increase in CCP can be used in existing reactors to offset reductions in thermalhydraulic margin resulting from reactor ageing phenomena after many years operation, such as steam generator fouling and diametral creep of the pressure tubes [2]. The higher CCP, and higher power capability of the bundle can also be utilized to increase core power output, particularly in a new reactor [3].

The CANFLEX bundle has been under development by AECL since the mid 1980's. In the early 1990's, the Korea Atomic Energy Research Institute (KAERI) joined AECL in a collaborative program to verify and qualify the CANFLEX fuel. The CANFLEX bundle has completed an extensive qualification program of analysis and testing, drawing on the capabilities of AECL's facilities in Canada and KAERI's facilities in Korea. In Canada, AECL's Chief Engineer conducted a formal design review to confirm the bundle's readiness for full-core implementation. Industry experts from New Brunswick Power, Hydro Québec, Ontario Power Generation, the two domestic fuel fabricators, and subject-area experts reviewed the qualification program and determined that the product was ready for implementation. In Korea, KAERI prepared a Fuel Design Report on CANFLEX-NU, submitted it to the Korea Institute of Nuclear Safety (KINS) and obtained approval of the fuel design and fabrication. A demonstration irradiation in the Wolsong 1 reactor in Korea is currently underway, following a similar successful irradiation in the Pt. Lepreau reactor in Canada.

While the CANFLEX Mk IV bundle is ready for commercial implementation, AECL is currently qualifying the CANFLEX Mk V version, which has slightly higher bearing pads than Mk IV. Raising the bearing pads results in a decrease in the overall eccentricity of the bundle string resting on bottom of a crept flow channel, and an increase in flow areas of subchannels facing the bottom of the pressure tube, which further improves CHF and CCP.
Figure 1 illustrates the dryout power performance of the CANFLEX bundle string relative to the 37-element bundle string, as a function of maximum pressure tube diametral creep, for two bearing pad heights of 1.4 mm and 1.7 mm. For the same channel flow, inlet temperature and system pressure conditions, the dryout power enhancement (% increase in dryout power relative to the 37-element bundle string) of the CANFLEX bundle string with the 1.4 mm bearing pad height ranges from 4% in an uncrept pressure tube, to 17% in a crept pressure tube with 5.1% maximum creep. The corresponding dryout power enhancements for the CANFLEX bundle string with the 1.7 mm bearing pads increase further to 10% and 25%, respectively. Overall, the pressure drop characteristics are similar for both the CANFLEX and 37-element bundle strings [4].

3. Slightly Enriched Uranium (SEU) / Recycled Uranium (RU)

The CANFLEX fuel bundle is the chosen carrier for SEU, not only for the improved thermalhydraulic performance that it offers, but also because the lower ratings reduce fission gas released to the free inventory. The lower fission-gas inventory results in lower element gas pressure, which enables higher burnups and reduces the consequences of most design-basis accidents. The lower ratings also increase the margins to failure from power ramps (or stress corrosion cracking [SCC] / pellet-clad interaction [PCI]). The use of SEU offers several potential benefits. Enrichment around 0.9% increases fuel burnup to about 14 MWd/kg, roughly doubling that of natural uranium, while an enrichment of 1.2% roughly triples the burnup. For the original geological repository concept developed by AECL, doubling or tripling the burnup of CANDU spent fuel would reduce disposal costs by 20-30% [5]. Reducing spent fuel volume may also have an additional positive effect on public perception beyond any technical or economic benefit. SEU fuel also improves uranium utilization (the amount of energy derived from the mined uranium) by ~30%.

SEU is also expected to reduce front-end fuel cycle costs by 20-30%. The benefit may be even greater with recycled uranium (RU), from reprocessed spent PWR fuel.

The use of SEU also changes the axial power distribution, from the nominal cosine shape with natural uranium, to one that is skewed towards the refuelling end (inlet end) of the channel. This is expected to improve the CCP, further increasing thermalhydraulic operating margins [6].

Since the early 1990’s, the collaboration between AECL and KAERI on CANFLEX development has included studies on the use of SEU. Since 1994 AECL and British Nuclear Fuel plc (BNFL) have pursued a cooperation program to exchange information on SEU and RU. As part of this collaboration, 35 CANFLEX bundles are currently being fabricated from RU, for reactor physics tests in AECL’s ZED-2 reactor. In 2000 AECL and Nucleoelectrica Argentina S. A. (NASA, the Argentine electrical utility) initiated a collaborative program to study the feasibility of converting the Embalse CANDU reactor from NU to SEU fuel, to realize reduced operating costs and to provide a strategy for raising reactor power. The results from this assessment are expected later this year.

One focus of recent AECL studies on SEU has been fuel management schemes for enrichment around 0.9%. Assessments have been done of equilibrium refuelling, the transition from natural uranium to an SEU-fuelled core, and a demonstration irradiation of SEU fuel bundles in a natural uranium core [7-9].

Another application of SEU is to tailor reactivity coefficients. For instance, addition of a neutron absorber in the center of the bundle (with natural or depleted uranium), with SEU in the remainder of the bundle, reduces void reactivity [10]. The amount of neutron absorber and the enrichment level can be independently varied to give any value of void reactivity (including negative), and average bundle burnup. This fuel concept is termed “low void reactivity fuel” (LVRF), and may be of interest in those jurisdictions where a reduction in void reactivity can facilitate licensing.

4. CANDU/LWR Synergism

High neutron economy, a simple fuel bundle design, and on-line refuelling enable the CANDU reactor to complement an LWR system. A number of recycle options can be envisioned in which the fissile material remaining in the discharged LWR fuel is further burned in CANDU.

At one end of this spectrum of recycle options is conventional reprocessing. A full core of MOX fuel can be accommodated in existing CANDU reactors. The small, lightweight, simple bundle design simplifies CANDU MOX fuel fabrication compared to LWR MOX fuel, and reduces the fabrication cost. AECL maintains a program of MOX fuel fabrication and irradiation testing at its Chalk River Laboratories [11]. Among other objectives, this program is elucidating the effect of MOX fuel manufacturing parameters (such as plutonium homogeneity) on fuel performance [12]. Several MOX bundles have been, and continue to be irradiated in the NRU reactor. While MOX fuel from plutonium recovered from spent CANDU fuel is not economical (the plutonium content in spent CANDU fuel is low relative to spent LWR fuel), the CANDU MOX option using plutonium recovered from spent LWR fuel may be of interest where access to reprocessing is available.

The high neutron economy of CANDU makes variants of reprocessing particularly attractive. Since the fissile content of spent LWR fuel is appropriate for use directly in CANDU without readjustment, then why separate the plutonium from the uranium, only to recombine them? With CANDU MOX fuel, the plutonium and uranium can be co-precipitated. This would increase the proliferation resistance of the process, and improve the economics. Given the relative ease of remote CANDU fuel fabrication, further simplifications and enhancement of the proliferation resistance could be achieved by selectively removing only the rare-earth neutron absorbing fission products. The remaining fission products and actinides would pose a radiation barrier against diversion.

An even higher degree of proliferation resistance could be achieved through a class of fuel recycle options involving only dry, thermal-mechanical processes, with no selective isotopic removal. The DUPIC cycle is one such example (Direct Use of Spent PWR or BWR Fuel In

CANDU) used to convert the spent PWR pellets into "new" CANDU pellets [13]. In the collaborative DUPIC program involving AECL, KAERI, and the U.S. Department of State (the IAEA also participates in the project review meetings), three full-size DUPIC fuel elements have been fabricated by AECL and irradiated in the NRU reactor. Two of these elements have been discharged at burnups of 10 and 15 MWd/kg, while the third element will achieve its target burnup of 21 MWd/kg later this year. PIE of the first DUPIC element has been completed, and confirmed good fuel performance [14]. KAERI has finished fabrication of 10 elements worth of DUPIC fuel pellets for additional irradiation testing.

The DUPIC fuel cycle offers a number of benefits:

- reduction in uranium requirements in an equilibrium system of CANDU and PWR reactors by 30% compared to an all-PWR system
- reduction in LWR spent fuel storage requirements
- reduction in quantity of fuel requiring disposal (In an equilibrium system of CANDU reactors and PWRs, the DUPIC cycle allows a 3-fold reduction in the quantity of spent fuel arisings per unit electricity generated, compared with direct disposal in a dual open operating system, in which CANDU reactors are fuelled with natural uranium and PWRs are fuelled with enriched uranium. The DUPIC system results in a 30% reduction in spent fuel arisings relative to PWR fuelling alone.)
- reduction in heat load of the spent fuel (per unit of electricity produced), through transmutation of higher actinides, and removal of the Cs in the original spent PWR fuel (the Cs could be stored above ground, where it would decay prior to disposal)
- transformation of the large, complex PWR fuel assembly into the simpler CANDU bundle for disposal
- favourable economics relative to conventional reprocessing based on preliminary assessments [15-18]
- high degree of proliferation resistance.

5. Parallex

The Parallex Project is a parallel experiment demonstrating the use of weapons-derived plutonium from the United States and Russia in CANDU MOX fuel elements [19]. The project was initiated in 1996 May, and is funded by the U.S. Department of Energy (DOE) in cooperation with the Canadian and Russian governments, and managed on behalf of the U.S. DOE by the Oak Ridge National Laboratory. The project builds on existing CANDU MOX fuel experience that has been acquired over 30 years of R&D at AECL, related to MOX fuel irradiation performance and fabrication development.

The objectives of the Parallex Project are twofold:

- to contribute to the database that would eventually qualify MOX fuel for use in CANDU reactors, and
- to demonstrate the feasibility of the infrastructure involved in the disposition of excess weapons plutonium as MOX fuel in CANDU reactors.

CANDU MOX fuel, containing weapon-grade PuO_2, has been fabricated at the A.A. Bochvar Institute in Russia, and at the Los Alamos National Laboratory in the U.S. The MOX fuel was transported to Canada in 2000, and testing of the fuel in the NRU research reactor at the Chalk

River Laboratories began in 2001 February. The test conditions in NRU will bracket those expected in a CANDU power reactor and provide meaningful data on performance of the MOX fuel. The test will also produce data showing how production and processing variables, as well as the detailed design of the pellets themselves, affect the performance of the CANDU MOX fuel. These comparisons will also be used to optimize the CANDU MOX fuel specifications and fabrication methods.

The Parallex experiment includes a total of three MOX fuel bundles. MOX fuel elements in the first bundle, manufactured in both the U.S. and Russia, have so far achieved a burnup of 13 MWd/kgHE, and are expected to complete their irradiation in early 2003.

Although only small quantities of MOX fuel are being tested in the NRU research reactor, the regulatory and logistical infrastructure required to utilize excess weapons plutonium as MOX fuel are being demonstrated as part of the Parallex Project. This is an important first step towards demonstrating the feasibility of dispositioning weapons-derived Pu as MOX fuel in CANDU reactors.

6. Thorium Fuel Cycles

The features of the CANDU reactor facilitate the introduction and full exploitation of thorium fuel cycles in CANDU reactors in an evolutionary fashion. The thorium fuel cycle in CANDU reactors is of strategic interest for several reasons [20].

In thorium fuel, U-233 is produced in-reactor through neutron capture in Th-232, and subsequent beta decay of Th-233 and Pa-233. The concentration of fissile U-233 in the spent fuel is about 5 times higher than that of Pu-239 in spent natural uranium UO_2 fuel in CANDU. This isotope of uranium is a very valuable fissile material because of the high number of neutrons produced per neutron absorbed (η) in the thermal neutron spectrum of CANDU reactors. However, since thorium has no fissile component, a source of fissile material must be provided to initiate, and unless the cycle is self-sufficient or breeding, to maintain the cycle. How this fissile material is provided defines a large range of possible thorium fuel cycles. High neutron economy and on-line fuelling result in several options being available in CANDU.

The abundance of thorium in the earth's crust is about 3 times that of uranium; thus the thorium fuel cycle ensures a long-term supply of nuclear fuel. Countries with abundant thorium reserves can enhance both the sustainability of nuclear power and their degree of energy independence. In the limit, the self-sufficient equilibrium thorium (SSET) cycle in CANDU is independent of natural uranium and of any external supply of fissile material. This, however, is a long-term thorium fuel cycle that requires recycle of the U-233. Another long-term thorium fuel cycle option would utilize fast breeder reactors to produce U-233, which would fuel several high-conversion-ratio CANDU reactors.

One attraction of the CANDU reactor for utilizing thorium is the existence of near-term, once-through thorium (OTT) fuel cycles, that enable energy to be derived from thorium today in an economical fashion, while U-233 is produced and safeguarded in the spent fuel, for future recycle.

ThO_2 (thoria) also has attractive physical properties: its thermal conductivity is about 50% higher than that of UO_2 over a large temperature range, and its melting temperature is 340ºC higher than that of UO_2. As a consequence, fuel-operating temperatures will be lower than those of UO_2, and fission-gas release from the fuel is expected to be lower than for UO_2 operating at similar ratings. ThO_2 is chemically very stable, and it does not oxidize—a benefit for normal operation, postulated accidents, and in waste management.

Th-232 produces fewer minor actinides than does U-238, and the radiotoxicity of spent thorium fuel is lower than for spent UO_2, which may be seen to be a benefit in waste management. (It should be noted, however, that in an engineered geological disposal vault in a reducing environment, the actinides contained in used fuel are not a significant contributor to radiological risk.)

In thorium recycle options, the daughter products of U-232 and Th-228 emit hard gammas, which, while necessitating remote fabrication, increase the proliferation resistance of the cycle through the radiation field. Another similar benefit is the reduced plutonium production relative to UO_2.

To ensure the viability of the CANDU reactor in the long term, AECL maintains an ongoing program on thorium fuel cycles. This program includes fuel-cycle studies, reactor physics measurements, fabrication of thorium fuels, irradiation in NRU followed by PIE, and assessments of fuel performance and waste management.

Recent work has focused on near-term thorium fuel cycles, fabrication techniques for thorium fuel, and NRU irradiations of thorium fuels.

Two near-term fuel cycles have been examined for burning thorium fuel in an existing CANDU 6 reactor. In the *mixed channel* once-through thorium fuel cycle, some of the fuel channels in the reactor would be fuelled with thoria and some with SEU "driver" fuel. This would allow independent optimization of fuelling rates for the SEU and thoria fuel, with the thoria remaining in the reactor much longer than the SEU, to allow for optimal in-reactor production and burning of the U-233.

Another type of fuel cycle considered is the *direct self-recycle* [21]. This is an extension of a once-through cycle that takes advantage of the simple fuel bundle design. In this cycle, some portion of the bundle, say the central 8 elements of a CANFLEX fuel bundle, would be made up of thoria. The rest of the bundle would comprise SEU driver fuel. After the bundle had reached its burnup target and had been discharged from the reactor, the bundle would be disassembled, fresh SEU driver fuel elements would replace the irradiated SEU, and the irradiated thoria fuel elements would be recycled in a reconstituted bundle that would be reinserted into the reactor. This would allow recycling of the thoria while maintaining a high degree of proliferation resistance, with no chemistry involved, no access to the fuel pellets, and no altering of the fuel element. It would also be much cheaper than reprocessing technology. Examples of such technology already exist in the "demountable bundle", that has been used for many years for fuel irradiations in the NRU loops, and in the "advanced carrier bundle", designed for irradiating fuel channel specimens in a commercial CANDU power reactor [22]. Furthermore, this cycle would create an inventory of U-233, safeguarded in the spent fuel, available for future recovery using proliferation-resistant technology.

Physics calculations have shown that it may be possible to provide a 25% improvement in uranium utilization with the direct self-recycle fuel cycle described. There is also considerable room for optimizing the fuel cycle to different criteria by varying the ratio of uranium to thorium, adding initial fissile material to the thorium, varying the enrichment of the uranium elements, etc.

AECL has conducted an extensive program to develop thoria fuels for CANDU reactors. This includes fabrication development, test irradiations, and performance assessments. While a lot of work was completed in the mid-1980s, more recent fabrication development activities at AECL have resulted in an improved ability to control the microstructure of thoria fuel. Pure ThO_2 and $(Th,U)O_2$ pellets have been fabricated and are being irradiated in the DME-221 experiment in NRU. This experiment will demonstrate the effect of controlled microstructure on thoria fuel performance. The irradiation has now been completed, and PIE will take place in 2003.

7. Summary

The inherent characteristics of the CANDU reactor and its fuel result in the most resource-efficient nuclear reactor. A variety of advanced fuel cycles can be utilized to meet a broad range of objectives. AECL's fuel and fuel cycle program provides a strong base to support the introduction of advanced CANDU fuel technology.

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Figure 1: Dryout power enhancement of CANFLEX design relative to the 37-element design, as a function of maximum diametral pressure tube creep and bearing pad height