

## **Fuel Cycles in CANDU: Security of Supply and Reduced Used Fuel Management**

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### **Abstract**

AECL has had a continuous fuel cycle program for more than 40 years, and anticipates that the next step in the evolution of CANDU fuel cycles will be the introduction of Recovered Uranium (RU), derived from conventional reprocessing. A low-risk RU option that can be applied in the short term comprises a combination of RU and Depleted Uranium (DU), giving a Natural Uranium Equivalent (NUE) fuel. Additionally, work is being done on a Thorium demonstration irradiation and a Thorium-capable CANDU Reactor (TCR). AECL has developed the Enhanced CANDU 6<sup>®</sup> (EC6<sup>®</sup>) reactor, upgraded from its CANDU 6 design. High neutron economy, on-power refueling and a simple fuel bundle provide the EC6 with the flexibility to accommodate a range of advanced fuels, in addition to its standard natural uranium.

### **1. Introduction**

There is a growing global trend towards extending nuclear fuel resources and reducing spent fuel through the application of fuel cycles. Drivers for fuel-cycle applications include security of fuel supply at a known (steady) price, energy independence and reduction of back-end spent fuel, with concomitant electricity production. CANDU<sup>®</sup> reactors exhibit superior fuel cycle flexibility, and are expected to play an important role in the future. Minimal design changes are required to use the proposed future fuel cycles. Atomic Energy of Canada Limited (AECL) has significantly evolved its CANDU reactor [1], streamlined construction techniques on an ongoing basis and developed and tested new fuel cycle options, which will be key to ensuring nuclear fuel resources and reducing waste in the future. Now operating successfully on four continents, CANDU technology can be easily localized—due to a core comprised of a large number of small, identical fuel channel components—and has demonstrated on-time and on-budget construction.

### **2. Fuel Cycles—Drivers**

In recent years, there has been a substantial growth in interest in advanced fuel cycles. Some key drivers for fuel cycles with low uranium consumption are:

Uranium prices are trending upward. Low-uranium consumption fuel cycles now have a real effect on LUEC. Potential customers are also mindful of their exposure to possible additional increases in the price of uranium, raising their interest in fuel cycles with improved uranium resource utilization.

Uranium supply/demand has not been a major concern in the past. As we enter the nuclear renaissance, however, there is potentially huge growth in the rate of uranium consumption, driven by some scenarios that show a six-fold increase in world energy usage by 2100 (with astronomical potential in China and India). Some estimates of the potential growth rates and resource availability suggest that there should be concern over uranium supplies within the lifetime of reactors now being built, with demand potentially exceeding supply as early as 2025.

Uranium availability is not uniform. Some countries have an abundance of the resource, while others have virtually none (but, occasionally, with substantial thorium, whose abundance is about three times that of uranium). Now, however, this has increased in importance with the new pressures on uranium prices and abundance, and increased concerns over domestic energy security.

Recovered Uranium (RU) from conventional reprocessing can become a concern as RU inventories are driven up by the separation plants required to deal with Pu and actinides. If, however, the processes actually generate reactor fuel, the economics can look attractive. Indeed, RU is now being looked upon as a resource or a commodity [2], rather than a waste product. AECL hosts an annual workshop with international participants to promote commercial RU use. RU (and its variants) in CANDU reactors requires no re-enrichment and has been shown to be remarkably insensitive to the presence of  $^{234}\text{U}$  and  $^{236}\text{U}$ .

Minor actinides are also a concern to many waste management scenarios. The technical limit on the capacity of most geological repositories is determined by decay heat-load. Many of the actinides (in particular  $^{241}\text{Am}$ ) are long-lived and generate enough heat to limit the capacity of a repository. Fuel cycles with the ability to “burn” (transmute) minor actinides into less problematic nuclides are beginning to look attractive. We have shown that a CANDU can be a very effective thermal burner of actinides [3, 4]. A CANDU thermal burner would have well-understood capital costs and be based on current technology, available to begin actinide burning much sooner.

### **3. CANDU—A Fuel Cycle Delivery System**

Key CANDU reactor features facilitating the application of fuel cycles include excellent neutron economy, on-power fuelling, a simple fuel bundle and fuel channel design. AECL has had a continuous fuel cycle program and vision [5-7] for more than 40 years, including: reactor physics and core design, fuel design and fabrication, irradiation and demonstration, reprocessing and separation, cycle optimization and commercial deployment options. The advanced CANFLEX<sup>TM</sup> fuel bundle [8, 9] has been developed as the optimal fuel carrier.

### **4. CANDU Fuel Cycle Applications**

AECL anticipates that the next step in the evolution of CANDU fuel cycles will be the introduction of Recovered Uranium (RU), and its variants, derived from conventional

reprocessing. A demonstration irradiation is well underway, with Chinese partners. Additionally, preliminary work is being done on the thorium cycle, including feasibility of a demonstration irradiation and development of a purpose-designed thorium-capable CANDU reactor. And, recent considerable attention paid to CANDU as a “burner” of the transuranic (TRU) actinide waste that comes from reprocessing used LWR fuel.

#### **4.1 Recovered Uranium**

Recovered Uranium (~0.9% enriched) from reprocessed LWR fuel can be used in CANDU without re-enrichment—offering an economical supply of LEU fuel at the optimal enrichment level [10]. The enrichment level is dictated primarily by the limit placed on fuel discharge burnup.

A low-risk RU option that can be applied in the short term, and is now being demonstrated by AECL and its Chinese partners, blends RU and Depleted Uranium (DU), giving an NU equivalent (NUE). NUE can increase effective burnup and reduce the coefficient of void reactivity, as well as reducing used fuel volumes. Twenty four NUE fuel bundles in two Qinshan unit 1 channels comprise the demonstration; the first four bundles were removed 2010 October 12, as planned. Liquid zone control levels and channel/zone power have not shown any abnormal changes during the irradiation; similarly for channel and bundle powers. Post-Irradiation Examination (PIE) will commence in early summer.

We are now examining a full core commercial NUE conversion, and reviewing various scenarios involving transition from NU to NUE, and mixed NU/NUE cores. Both 37-element and CANFLEX options are under study, with various fuel options in the bundle rings, including the possible application of burnable absorbers.

This fuel cycle—providing the ability to burn two former waste products (RU and DU) now regarded as resources without re-enrichment—differentiates CANDU plants from all other nuclear options. CANDU plants offer the simplest and most cost-effective way of burning these products. The RU/DU cycle is the first and the simplest demonstration of CANDU fuel cycle flexibility and a major step on the road to thorium cycles.

#### **4.2 Thorium Cycles**

Thorium is a key element in AECL’s fuel cycle vision for CANDU and represents a low-uranium-consumption fuel cycle option [11-14]. A thorium-fuelled CANDU would be attractive to countries with thorium reserves but no uranium—addressing the need for energy self-reliance.

Possible CANDU thorium fuel cycles include open cycles, such as a Once-Through Thorium (OTT) cycle, and closed cycles, which involve reprocessing used fuel and ultimately recycling the separated  $^{233}\text{U}$ . Fissile driver fuel must be added to the thorium to initiate and sustain the chain reaction and to breed  $^{233}\text{U}$  through neutron capture and

subsequent beta decay. Fissile material can be provided by existing plutonium (Pu) stocks, enriched uranium or from fast breeder reactors (FBRs).

The short-term [10], low-risk approach to initiating the thorium fuel cycle in a CANDU reactor is by adding the fissile component as LEU in separate elements in a mixed LEU/Th fuel bundle, using an existing fuel design, such as the conventional 37-element bundle, or the CANFLEX bundle. The enrichment of the LEU elements is varied to give the desired burnup. Benefit is derived from the *in-situ* fissioning of the  $^{233}\text{U}$  produced through neutron capture in  $^{232}\text{Th}$ , thus also building up a strategic resource of  $^{233}\text{U}$  for future application.

The major economic benefit derives from closed thorium cycles. In the medium term [10], used LWR fuel is reprocessed. This presents an opportunity for further improvements in resource efficiency and for exploiting the synergism between CANDU reactors and Light Water Reactors [LWRs]. The plutonium from reprocessed LWR fuel can be used as the fissile component in a homogeneous Pu/Th CANDU fuel bundle. A full core of Pu/Th fuel could further increase the energy derived from utilizing thorium, require no new natural uranium, and produce additional  $^{233}\text{U}$  in the used fuel for future recovery and recycling.

In the longer term [11], a self-sufficient thorium fuel cycle is the most economically attractive, breeding enough  $^{233}\text{U}$  for recycle, to keep the cycle running indefinitely, without the need for an additional, external supply of fissile material. This is a longer-term timeframe because of the complication of recycling  $^{233}\text{U}$  from the irradiated thorium fuel. In the distant future, one could envisage a CANDU-FBR synergism, allowing a few expensive FBRs to supply the fissile requirements of less-expensive, high-conversion-ratio CANDU reactors operating on the thorium cycle.

Currently, AECL is exploring the feasibility of a multi-bundle thorium demonstration irradiation, employing the low-risk option described above. Fuel options being examined include both 37-element and CANFLEX bundles with Nu/Th and LEU/Th. Thorium code validation work is producing promising results. The next logical step is a full-core demonstration. At the same time, AECL is initiating the conceptual design of a purpose-designed thorium-capable CANDU reactor, based on the C6/EC6 platform.

### **4.3 Actinide Destruction**

Recently, there has been considerable attention paid to CANDU as a “burner” of the transuranic (TRU) actinide waste that comes from reprocessing used LWR fuel [2, 3, 15]. Many TRU actinides are long-lived (e.g., Am, Cm, Np) and produce decay heat long after being discharged from the reactor. This decay heat provides waste management challenges, including the management of extended heat loading of storage/disposal facilities. CANDU’s neutron economy results in a high TRU destruction rate, and on-power fuelling permits the optimum location and residence time of actinide targets.

Homogeneous and heterogeneous bundles and cores are being examined for feasibility. One CANDU option actually addresses three problematic streams: the Am inventory in

the US exceeds 25 tonnes; it requires extended duration monitoring, and heat generation dictates the amount that can be placed in a disposal facility; the inventory of separated civilian-grade Pu; and 500,000 plus tonnes of DU defined as low-level waste. Actinide MOX containing Am, Pu and DU can be used as a CANDU fuel. A homogeneous full core loading gives an exit burnup of about 20 MWd/kgHE; Am transmutation up to 680 kg/year; Pu consumption up to 980 kg/year and DU consumption of about 38 tonnes/year.

## **5. Summary**

As countries strive for energy self-sufficiency, seek stable and known fuel prices, and seek to simplify used-fuel management, drivers arise leading to a continuing evaluation of fuel cycles. Current-technology thermal reactors and future fast reactors are the preferred platforms for such fuel cycle applications and as an established thermal reactor with unique fuel-cycle capability, CANDU will play a key rôle.

A low-risk RU option that can be applied in the short term, and is now being demonstrated by AECL and its Chinese partners, blends RU and Depleted Uranium (DU), both (former) waste streams, giving an NU equivalent (NUE), and the feasibility of a full-core conversion is being examined. Currently, AECL is exploring the feasibility of a multi-bundle thorium demonstration irradiation, employing a low-risk OTT option; work is also underway on a purpose-designed thorium-capable CANDU reactor. And, CANDU is most efficient as a “burner” of the transuranic (TRU) actinide waste that comes from reprocessing used LWR fuel, and increases the challenge for managing storage and disposal of used fuel (HLW).

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