Int. Conf. Future of HWRs **Paper 026**
Ottawa, Ontario, Canada, Oct. 02-05, 2011

Fuel Cycles—A Key to Future CANDU Success

Sermet Kuran, Jerry Hopwood and Ian J. Hastings
Atomic Energy of Canada Limited, Mississauga, Ontario L5K 1B2, Canada

Abstract

Globally, fuel cycles are being evaluated as ways of extending nuclear fuel resources, addressing security of supply and reducing back-end spent-fuel management. Current-technology thermal reactors and future fast reactors are the preferred platform for such fuel cycle applications and as an established thermal reactor with unique fuel-cycle capability, CANDU®* will play a key rôle in fulfilling such a vision.

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 applicable in the short term comprises a combination of RU and Depleted Uranium (DU), both former waste streams, giving a Natural Uranium Equivalent (NUE) fuel. This option has been demonstrated in China, and all test bundles have been removed from the Qinshan 1 reactor. Additionally, work is being done on an NUE full core, a Thorium demonstration irradiation and an Advanced Fuel CANDU Reactor™ (AFCR™). AECL is developing other fuel options for CANDU, including actinide waste burning.

AECL has developed the Enhanced CANDU 6®* (EC6®*) reactor, upgraded from its best-performing 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 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. Why Fuel Cycles?

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

- Uranium prices are on the upward trend. Low-uranium consumption fuel cycles now have a real effect on LUEC. Potential customers realize their exposure to possible additional increases in the price of uranium, raising their interest in improving uranium resource utilization.
- Uranium supply/demand. However, there is potentially significant growth in uranium consumption, driven by some scenarios that show substantial increase in world energy usage by 2100 (especially China and India).
- Uranium availability varies. 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).
- Recovered Uranium (RU) from conventional reprocessing was a concern as RU inventories are driven up by the separation plants required to deal with Pu and actinides. However, RU is now being looked upon as a resource or a commodity [2], rather than a waste product. RU (and its variants) in CANDU reactors requires no re-enrichment and has been shown to be remarkably insensitive to the presence of ^{234}U and ^{236}U.
- Minor actinides are also a concern in waste management scenarios. Actinides (in particular ^{241}Am) are long-lived and generate enough heat to limit the capacity of a repository. Fuel cycles in a reactor with the ability to “burn” (transmute) minor actinides into nuclides are beginning to look attractive. A CANDU can be a very effective thermal burner of actinides [3, 4]; such a thermal burner has well-understood capital costs and is based on current technology.

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™ fuel bundle [8, 9] has been developed as the optimal fuel carrier.

4. CANDU Fuel Cycle Applications

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 of light water reactor (LWR) fuel. A demonstration irradiation is complete, with AECL's Chinese partners. Additionally, preliminary work is being done on the thorium cycle, including feasibility of a demonstration irradiation and development of a purpose-designed Advanced Fuel CANDU Reactor (AFCR). And, recent considerable attention has been 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]. A low-risk RU option that can be applied in the short term, and has been 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 comprised the demonstration; all bundles have been removed 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 2011 summer.

AECL is 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.

This RU fuel cycle, directly using two former waste products (RU and DU) 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 longer-term 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, satisfying 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}U. Fissile driver fuel must be added to the thorium to initiate and sustain the chain reaction and to breed ^{233}U through neutron capture and subsequent beta decay. Fissile material can be provided by existing plutonium (Pu) stocks, low enriched uranium (LEU), 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}U produced through neutron capture in ^{232}Th, thus also building up a resource of ^{233}U for future application.

The major economic benefit is achieved in closed thorium cycles. In the medium term [10], 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}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}U to keep the cycle running indefinitely, without the need for an additional, external fissile supply. This is a longer-term timeframe because of the complication of recycling ^{233}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 OTT 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 AFCR, based on the C6/EC6 platform.

4.3 Actinide Burning

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 a challenge in 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. One CANDU option addresses three problem streams: i) the Am inventory in the US exceeds 25 tonnes; it requires extended duration monitoring, and heat generation limits the amount that can be placed in a disposal facility; ii) the inventory of separated civilian-grade Pu; and iii) 500,000 plus tones 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, stable fuel prices, and simplified used-fuel management, drivers lead to an ongoing 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 fuel option that can be applied in the short term, and has been demonstrated by AECL and its Chinese partners, blends RU and Depleted Uranium (DU), both (former) waste streams, giving an NU equivalent (NUE); the feasibility of a full-core NUE conversion is being examined. Currently, AECL is exploring a multi-bundle thorium demonstration irradiation, employing the low-risk OTT option; work is also underway on an AFCR. And, CANDU is most efficient as a “burner” of the TRU waste that comes from reprocessing used LWR fuel, and can simplify the challenge for managing storage and disposal of used fuel.

6. References

[1] J. Hopwood, I.J. Hastings, and M. Soulard, “Enhanced CANDU 6 (EC6): A Proven Mid-Sized Reactor with Fuel Cycle Capability”, CNS Annual Conference, Niagara Falls, Ontario, 2011 June 5-9.

[2] AREVA 2009, “More Energy less CO_2”, Responsible Growth Report, p. 56ff, 2009.

[3] B. Hyland and G.R. Dyck, “Actinide Burning in CANDU Reactors”, Proceedings Global 2007 Conference on Advanced Nuclear Fuel Cycles and Systems, Boise, USA.

[4] B. Hyland and B. Gihm, “Scenarios for the Transmutation of Actinides in CANDU Reactors”, Proceedings of the 18th International Conference on Nuclear Engineering, ICONE18, Xi'an, China, May 17-21, 2010.

[5] P. Chan, G. Dyck, S. Kuran, M. Ivanco, J. Hopwood and I.J. Hastings, “Fuel Cycles—Secure Supply, Reduced, Enhanced Non- Proliferation”, Proceedings, 16th Pacific Basin Nuclear Conference, Aomori, Japan, 2008 October 13-18.

[6] J. Veeder and R. Didsbury, “A Catalogue of Advanced Fuel Cycles in CANDU Reactors”, Atomic Energy of Canada Limited report, AECL-8641, 1985 June.

[7] J. Hopwood, S. Kuran and I.J. Hastings, “Fuel Cycles in CANDU: Security of Supply and Reduced Used Fuel Management”, CNS Annual Conference, Niagara Falls, Ontario, 2011 June 5-9.

.

[8] R.E. Green, P.G. Boczar and I.J. Hastings, "Advanced Fuel Cycles for CANDU", Proc. 28th Annual Canadian Nuclear Association Conf., Winnipeg, Canada, 1998.

[9] W.W.R. Inch, P.D. Thompson and Suk, H.C., "Introduction of the New Fuel Bundle CANFLEX into an Existing CANDU Reactor", Proceedings, 12th Pacific Basin Nuclear Conference, Seoul, Korea, 2000.

[10] P.G. Boczar, *et al.*, "Recovered Uranium in CANDU: A Strategic Opportunity", Proceedings INC 93: International Nuclear Congress, Canadian Nuclear Society, Toronto, Canada, 1993.

[11] P.G. Boczar, P.G.., *et al.* "Recent Advances in Thorium Fuel Cycles in CANDU Reactors", IAEA TECDOC-1319, Vienna, Austria, 2002.

[12] J. Hopwood, *et al.*, "CANDU Reactors with Thorium Fuel Cycles", Proceedings, 15th Pacific Basin Nuclear Conference, Sydney, Australia, 2006.

[13] J. Mao, P. Chan and S. Kuran, "Fuel Management Simulations of Thorium Fuel Cycle in CANDU 6 Reactors", Proceedings Advances in Nuclear Fuel Management IV, Hilton Head, USA, 2009.

[14] P.G. Boczar, B. Hyland, K. Bradley and S. Kuran, S., "Achieving Resource Sustainability in China through the Thorium Fuel Cycle in the CANDU Reactor", Proceedings of the 18th International Conference on Nuclear Engineering ICONE18 May 17-21, 2010, Xi'an, China.

[15] E.D. Collins, C.W. Alexander, D.E. Benker and J.P. Renier, J.P., "Analogies of Experience in the U.S. Transuranium Element Production Program with Partitioning and Transmutation of Transuranic Actinides in Commercial Used Fuels", 11th IEMPT, San Francisco, CA, 2010 November 1-5.