CANDU 6: VERSATILE AND PRACTICAL FUEL TECHNOLOGY

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ABSTRACT

CANDU® reactor technology was originally developed in Canada as part of the original introduction of peaceful nuclear power in the 1960s and has been continuously evolving and improving ever since. The CANDU reactor system was defined with a requirement to be able to efficiently use natural uranium (NU) without the need for enrichment. This led to the adaptation of the pressure tube approach with heavy water coolant and moderator together with on-power fuelling, all of which contribute to excellent neutron efficiency. Since the beginning, CANDU reactors have used NU fuel as the fundamental basis of the design. The standard NU fuel bundle for CANDU is a very simple design and the simplicity of the fuel design adds to the cost effectiveness of CANDU fuelling because the fuel is relatively straightforward to manufacture and use. These characteristics -- excellent neutron efficiency and simple, readily-manufactured fuel -- together lead to the unique adaptability of CANDU to alternate fuel types, and advancements in fuel cycles. Europe has been an early pioneer in nuclear power; and over the years has accumulated various “waste” products from reactor fuelling and fuel reprocessing, all being stored safely but which with passing time and ever increasing stockpiles will become issues for both governments and utilities. Several European countries have also pioneered in fuel reprocessing and recycling (UK, France, Russia) in what can be viewed as a good neighbor policy to make most efficient use of fuel. The fact remains that CANDU is the most fuel efficient thermal reactor available today; NU; more efficient in MW per ton of U compared to LWR’s and these same features of CANDU (on-power fuelling, D2O, etc) also enable flexibility to adapt to other fuel cycles, particularly recycling. Many years of research (including at ICN Pitesti) have shown CANDU capability: best at Thorium utilization; can use RU without re-enrichment; can readily use MOX. Our premise is that CANDU can be deployed in Europe to reduce waste, save money for operating utilities (i.e. Nuclearelectrica) and introduce much more flexible fuel options. This paper provides an update on recent developments in the application of CANDU to important fuel cycle options. More specifically we report on recent developments in three key areas:

- China – NUE – uses both RU and DU; two waste products to make fuel. Test irradiations done, moving to full-core implementation
- China - Thorium
- UK – MOX; CANDU is a leading contender and most efficient practical solution.

In the current context where nuclear power expansion remains under consideration for many countries as the primary greenhouse-gas-free energy option, the deployment of CANDU reactors for advanced fuel use provides important potential advantages, both on its own and in synergy with other elements of the global nuclear system.

I. Introduction

CANDU Reactor Technology Background

CANDU® reactor technology was originally developed in Canada as part of the original introduction of peaceful nuclear power in the 1960s and has been continuously evolving and improving ever since.

The CANDU reactor system was defined with a requirement to be able to efficiently use natural uranium (NU) without the need to enrichment. This led to the adaptation of the pressure tube approach with heavy water coolant and moderator together with on-power fuelling, all of which contribute to excellent neutron efficiency.

Since the beginning, CANDU reactors have used NU fuel as the basis. The standard NU fuel bundle for CANDU is a very simple design, approximately 50cm in length and 10cm in diameter. For the CANDU 6® design there are 12 bundles in each of the 380 fuel channels. The simplicity of the fuel design adds to the cost effectiveness of CANDU fuelling because the fuel is relatively straightforward to manufacture and use.

These characteristics -- excellent neutron efficiency and simple, readily-manufactured fuel -- together lead to the unique adaptability of CANDU to alternate fuel types, and advancements in fuel cycles.

This paper provides a progress report on recent developments in the application of CANDU to important fuel cycle options, including the underlying technology development and demonstration. In the current context where nuclear power expansion remains under consideration for many countries as the primary greenhouse-gas-free energy option, the deployment of CANDU reactors for advanced fuel use provides important potential advantages, both on its own and in synergy with other elements of the global nuclear system. CANDU reactors can employ advanced fuel cycles to:

- Extend the energy use from uranium – by using Recovered and Depleted Uranium stockpiles to create economical fuel
- Reduce long-lived waste quantities by transmuting actinides in an economical fuel adaptation; or by use of the thorium cycle with its lack of trans-uranic material generation
- Generate peaceful energy and use up strategically-important stockpiles of nuclear materials, e.g. by the efficient use of MOX fuel
- Enable the practical introduction of the Thorium fuel cycle to stabilize the overall long term fuel supply for nuclear systems

Using the Generation III Enhanced CANDU 6® (EC6®) as a base technology, Candu Energy is working on specific initiatives that can optimize reactor and fuel technologies in each of these areas. In addition, the introduction of alternate, cost-effective fuels into the current fleet of CANDU units is now ready for full scale introduction. Because the main changes to use alternative fuel cycles are made within the fuel itself, very little or no design change is needed to the EC6 core to enable alternate fuel use. Together with the extensive test and demonstration already undertaken with alternative fuels, this means that the overall introduction of alternative fuels involves relatively low risks to performance. CANDU represents a very well-proven and straightforward way to introduce new fuels into the nuclear fleet. The main step will be to introduce adapted fuel bundle designs such as the CANFLEX fuel bundle [1].

II. CANDU Alternate Fuel Development and Demonstration

Research, development and testing for alternate CANDU fuels have been underway since the 1960s, particularly at AECL's laboratories in Canada and at a number of other research centers [2]. From the initial development of the CANDU reactor system, alternate fuels have been designed, tested both in and out of reactor and demonstrated in parallel with the development of the reference NU fuel option. Of particular interest have been the following major development and test initiatives:

a) Enriched and Recovered Uranium
b) Fuels for DUPIC and TANDEM Fuel Cycles
c) MOX Fuels
d) Thorium Fuels

In addition, substantial development work has been undertaken on other fuel options such as inert-matrix fuels and fuels formulated to burn actinides.

The approach has been to:

- Bench test out fuel alternative materials in preparation for full scale testing
- Carry out tests that envelope existing experience with Natural Uranium fuels
- Develop test data to demonstrate performance at extended conditions, e.g. higher burn-up
- Complement other test programs elsewhere

Research has included: fuel test irradiations in research reactors, covering levels of burn-up, power and power boosts well outside the levels to be undergone in commercial reactors; thermal hydraulic tests to cover thermal margins for the range of fuel power distributions; mechanical testing to confirm fuel material capability with the different constituents; and testing of handling methods to fabricate fuels. This work is in parallel with the equally important development work worldwide to establish reprocessing technologies. The CANDU approach has been to establish fuel options that can be adopted today without the need for new reprocessing (e.g. by use of RU stockpiles) while preparing for a future where reprocessing is fully introduced.

This development work on fuel types has been accompanied by engineering and modeling work, including adaptation and validation of computer codes, to confirm the operating and safety characteristics of these fuels in CANDU reactors. The results of these preliminary studies have confirmed (e.g. [2], [3]):

- CANDU reactor designs require relatively minor design changes to be optimized to effectively use alternate fuel cycles
- Existing operating CANDU units can, with appropriate back fits (in particular cases with no back fits), transition to contain alternate fuel cycle options
- Effective and fuel-efficient applications of alternate fuels can be designed that
    - will operate within the performance envelopes supported by experimental programs so far
    - will have fuel and reactor characteristics within the existing CANDU NU safety envelope

III. Extending Fuel Cycles for Existing CANDUs

In the most prominent initiative today, Candu Energy has continued the well-established Canada-China cooperation in fuel cycle development via cooperative initiative with TQNPC, NPIC, and CNNFC originated by AECL. The complements the successful introduction and operation of the twin-unit CANDU 6 plant at the Qinshan Phase 3. This cooperation is aimed at developing commercial scale applications of two alternate fuels:

- Derivatives of Recovered Uranium fuel, starting with the early use of Natural Uranium Equivalent (NUE) fuel
- Thorium-based fuels to introduce the Thorium cycle at industrial scale

These two initiatives have very strong impacts in opening up the choice of fuel options. In each case, the fuel can be introduced to deliver an immediate economic benefit (reduced fuel cost) and environmental benefit (increasing energy generated per tonne of U used)—while also paving the way for further economic and environmental benefits as the concepts are developed onward in the future. NUE fuel is designed to combine recovered uranium and depleted uranium in precisely controlled proportions to provide the fissile and reactivity equivalent of natural uranium demonstration irradiations.

The approach used for NUE fuel can be extended to optimize the use of slightly enriched fuels in existing CANDUs. Previous studies have established the viability of the use of higher than NU enrichment in CANDU reactors [2,4]. Experimental and demonstration irradiations confirm fuel performance up to 20GWD/THE under CANDU conditions, and engineering studies have confirmed capability to refuel the reactor on-line with slightly enriched fuels while maintaining fuelling machine capability, reactivity balance and control, and maintaining fuel parameters within the existing safety envelope.

The formulation of fuel materials for "Low-Enriched" fuel bundles depends on: the type of mission intended; the requirements on fuel performance and safety parameters for regulatory approval; and the characteristics of the operating reactor. However, enrichment levels that provide efficient operation for the CANDU reactor core are much lower than for LWR's so that recovered uranium can be used as an SEU fuel without any re-enrichment.

As well as the use of conventional enriched uranium fuel, studies have been undertaken for the use of recycled material, particularly the joint Canadian-Korean program to test and demonstrate DUPIC fuel (Direct Use of PWR Fuel in CANDU) [5]. Tests of the fuel manufacturing process and irradiation of fuel elements demonstrated the viability of the option, and confirmed a number of safeguard benefits of the use of recycled PWR fuel in this way.

More generally, the option of extending the NUE approach to increasing levels of burn-up while remaining within the CANDU reactor and fuel safety and performance envelope is an achievable next step, based on most recent Candu engineering studies. Most importantly, the fully-comprehensive work to introduce the NUE fuel concept has demonstrated every stage of the path to full-scale use: fuel material control and preparation, pelletizing and fuel manufacturing; reactor operational and safety review; licensing and implementation of demonstration irradiation; preparation of full-scale safety case, and planning by all sides for industrial-scale use. This model is an example for the practical steps to introduce further alternative fuels into CANDU.

Optimizing the RU option for existing CANDU's is also being studied, since this has the promise of reducing fuel costs for current operators, with minimum investment at the reactor itself. Again, the existing R&D base provides the demonstration of a wide operating envelope so that there is a great deal of flexibility in tailoring RU-based fuels to operator priorities.

IV. CANDU Optimization for Advanced Fuel Cycles—Toward the AFCR Series

The ability to use alternate fuels, alongside the benefits of NU capability, is one of CANDU's key attributes in its role in future nuclear power planning. Candu Energy has brought the flagship CANDU 6 design up to the current state of the art as the EC6 design [6]. The EC6 is a fully Generation III level design which is based on incremental changes to the latest reference (Qinshan Phase 3) CANDU 6 operating units. The EC6 design therefore follows the same continuous improvement approach, and retains the provenness of the reference plant design. The EC6 has been reviewed by the Canadian regulatory authority through its rigorous Pre-Project Design Review Process and includes a comprehensive response to the issues arising from Fukushima.

The EC6 design continues with the standard reference NU fuel as its basis. However, given the extensive past studies that demonstrate the ready adaptability of CANDU design for fuel cycle optimization, the EC6 also provides a design platform for CANDU designs, again with incremental changes, tailored to client fuel cycle requirements—Advanced Fuel Cycle CANDUs, or AFCRs.

The AFCR concept is the heart of the joint development program for the application of CANDU to China's fuel cycle objectives.

Candu and its development partners TQNPC, NPIC and CNNFC are co-developing and demonstrating both fuel and reactor modifications to create a far-reaching comprehensive design option with the flexibility to meet evolving fuel priorities in expanding nuclear countries such as China.

The China AFCR will retain proven CANDU 6 characteristics while including design features for fuelling using RU-based fuels and also the ability to use TH-U fuels as a highly cost-effective and low-risk introduction of Thorium to the fuel cycle. Because of the innate flexibility in CANDU due to on-power refueling, only modest changes to core configuration and refueling route are required, while the rest of the plant will follow the well-established "continuous-improvement approach" based on the EC6 platform. In parallel with reactor design, fuel specifications and final qualification steps are also underway.

In a recent example, the adaptation of the proven EC6 design to an alternative fuel approach is also under study for a potential application in the UK. As an option for the disposition of the UK stocks of civilian plutonium for reprocessing, the use of CANDU to generate electricity using the Pu in MOX fuel has some important advantages:

- CANDU MOX fuel can make full use of DU as the fuel matrix for Pu, so that all the fission energy generation is concentrated in Plutonium, increasing the efficiency of the Pu disposition process
- CANDU MOX fuel can adopt lower fissile content, simplifying manufacturing and handling
- The simple CANDU fuel bundle is well suited to the specialist requirements of MOX fuel manufacture

Again, the EC6 platform requires minimal modification to receive the MOX fuel as a MOX-based AFCR type.

V. The Next Generation of CANDU – making full use of fuel cycle capability

The increasing interest in broadening the nuclear fuel cycle means there is an incentive to study how far the CANDU system can be stretched to make powerful use of its fuel efficiency. CANDU's are neutron-efficient because they have low levels of parasitic neutron absorption in the core, and because on-power fuelling means there is no need for high levels of neutron absorbers at the beginning of a reactor fuel cycle, as in LWR's for example. The use of heavy water as coolant and moderator further improves neutron efficiency. In the future, CANDU designs may be adapted to further reduce neutron absorption, and previous work has shown that the use of a closed thorium cycle can lead to a near-breeder design that uses only a tiny amount of added fissile material to achieve self-sufficiency; the ability to make use of the full complement of thorium to energy production [7]. CANDU reactor designs can also be adapted to focus on destruction of actinides as a part of their operation, should this be chosen as a waste management route.

The most beneficial way to consider deploying the next generation of CANDU's will be as part of an overall system of reactors and fuel cycle facilities, that would arise to respond to the challenges of fuel availability and spent fuel management. Studies have shown that CANDU's can play a role in combination with other reactor types and fuel cycle facilities, to create the most efficient overall treatment of fuel. CANDU's adaptability to use a range of fuels, and to alter fuelling approach during reactor life, mean that it can play a vital part in adapting overall industrial systems to varying priorities towards energy economics, long-term waste management, security etc. For example, a previous study showed that, if fast reactors were introduced in production scale, CANDU units could play the most beneficial role in using LWR waste as a first step before proceeding to their use in the fast reactor fleet [8].

V. Conclusions

The examination of fuel cycle challenges shows that the CANDU system can play a vital part both in the immediate term, and on into the longer-term future, to extend and open up fuel resources and to provide alternatives for the management of spent fuel and waste products. The ability of CANDU reactors to adapt to alternative fuels within a highly proven existing reactor design, provides an important advantage in reducing the risks and challenges of introducing alternate fuels.
These two examples are active demonstrations of the adaptability of the standard CANDU design to use alternate fuels.

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