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CANDU FUEL-CYCLE VISION

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Abstract

The fuel-cycle path chosen by a particular country will depend on a range of local and global factors. The CANDU® reactor provides the fuel-cycle flexibility to enable any country to optimize its fuel-cycle strategy to suit its own needs.

AECL has developed the CANFLEX® fuel bundle as the near-term carrier of advanced fuel cycles. A demonstration irradiation of 24 CANFLEX bundles in the Point Lepreau power station, and a full-scale critical heat flux (CHF) test in water are planned in 1998, before commercial implementation of CANFLEX fuelling. CANFLEX fuel provides a reduction in peak linear element ratings, and a significant enhancement in thermalhydraulic performance.

Whereas natural uranium fuel provides many advantages, the use of slightly enriched uranium (SEU) in CANDU reactors offers even lower fuel-cycle costs and other benefits, such as uprating capability through flattening the channel power distribution across the core. Recycled uranium (RU) from reprocessing spent PWR fuel is a subset of SEU that has significant economic promise. AECL views the use of SEU/RU in the CANFLEX bundle as the first logical step from natural uranium.

High neutron economy enables the use of low-fissile fuel in CANDU reactors, which opens up a spectrum of unique fuel-cycle opportunities that exploit the synergism between CANDU reactors and LWRs. At one end of this spectrum is the use of materials from conventional reprocessing: CANDU reactors can utilize the RU directly without re-enrichment, the plutonium as conventional mixed-oxide (MOX) fuel, and the actinide waste mixed with plutonium in an inert-matrix carrier. At the other end of the spectrum is the DUPIC cycle, employing only thermal-mechanical processes to convert spent LWR fuel into CANDU fuel, with no purposeful separation of isotopes from the fuel, and possessing a high degree of proliferation resistance. Between these two extremes are other advanced recycling options that offer particular advantages in exploiting the CANDU reactor's high neutron economy to reuse spent LWR fuel without the need to separate, then enrich the contained fissile material.

Thorium can provide a significant extension to uranium resources in the longer term. It is of shorter-term interest in those countries possessing extensive thorium resources, but lacking indigenous uranium reserves. The once-through thorium (OTT) cycle provides a bridge between current uranium-based fuel cycles, and a thorium fuel cycle based on recycle of ^{233}U. The optimal OTT cycle is economical today, in terms both of money and uranium resources. This cycle creates a mine of valuable ^{233}U, safeguarded in the spent fuel, for future recovery predicated by economic or resource considerations. AECL has recently devised practical OTT strategies.

1. INTRODUCTION

The IAEA-sponsored International Symposium on "Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities" identified the factors influencing the choice of fuel-cycle strategy, and development requirements and directions [1]. The fuel-cycle path chosen by a particular country or utility will depend on many local and global factors, a few of which are short-and long-term availability,

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cost, security, and diversity of energy resources; the state of industrial development; availability and cost of fuel-cycle technologies both domestically and off-shore (such as enrichment, and reprocessing); back-end considerations, including total inventories of spent fuel and high-level waste requiring permanent disposal, environmental impact, availability, cost, and public acceptance of permanent disposal facilities; government policy on energy and industrial development; and non-proliferation considerations. Given the historical difficulty in predicting the availability and cost of energy resources and fuel-cycle technologies, and the large uncertainties and variability in many of the factors, a superior nuclear energy strategy must include fuel-cycle flexibility. An inherent feature of the CANDU design is its very high degree of fuel-cycle flexibility. This enables a country, or utility, to optimize its fuel-cycle strategy based on its own unique circumstances. CANDU is an evolutionary reactor, offering a custom fuel cycle to fit local requirements.

2. CANDU FEATURES FACILITATING ADVANCED FUEL CYCLES

Several key features enable the CANDU reactor to meet the energy and fuel-cycle requirements far into the future. Two of these features are the channel design of the reactor, and on-power refuelling. The fuel channels are separated by relatively large amounts of heavy water. The spectrum of neutrons entering a channel is very well thermalized, and largely independent of the fuel type. On-power refuelling provides a great deal of flexibility in fuel management. Fuelling is bi-directional, meaning that adjacent fuel channels are refuelled in opposite directions. This method of fuelling results in both a flattening of the axial flux distribution, and a symmetrical axial flux distribution. The axial power distribution along the channel is mainly determined by the variation of reactivity along the channel, which itself is determined by the fuel type (particularly the initial enrichment), the fuel-management scheme, and the location of reactivity devices in the moderator (e.g., the adjuster rods). The variation of reactivity along the channel can be controlled in the simplest instance by varying the rate of refuelling; in most cases, this provides sufficient shaping of the axial power distribution, and results in similar axial power profiles for a wide variety of fuel types. The consequence is that slightly enriched uranium (SEU), mixed-oxide (MOX), thorium, and even inert-matrix fuels (containing no fertile material) can all be utilized in existing CANDU reactors. Moreover, the axial power distribution with enriched fuels peaks towards that end of the channel in which new fuel is added, and decreases along the length of the channel. For CANDU 6 and CANDU 9 reactors, in which fuelling is in the direction of coolant flow, the peak bundle power occurs towards the coolant inlet end of the channel. This axial power distribution results in higher thermalhydraulic margins than obtained with the more symmetric axial power distribution arising from natural uranium fuel, and the declining power history with burnup facilitates good fuel performance.

Ultimately, bundles can be removed from the channel during refuelling and reshuffled, and reinserted in any order. This axial shuffling provides nearly unlimited capability for shaping the axial power distribution, if necessary. Adjuster rods are located interstitially between fuel channels, in the low-pressure moderator. They flatten the power distribution with natural uranium fuel, a function not required with enriched fuel, and provide xenon-override capability. With enriched fuel, the adjuster rods can be easily replaced, if desired, or even eliminated, providing further flexibility in accommodating advanced fuel cycles.

The fuel-management scheme can also shape the radial channel power distribution across the core. With enrichment, the extra burnup potential can be traded off for increased power in the outer channels by "flattening" the channel power distribution, obtaining more power from a given sized core. Fuel-management flexibility also provides many options in the transition from one fuel type to another.

High neutron economy is another feature of the CANDU reactor that is key to fuel-cycle flexibility. The ability to use low-fissile fuel makes possible a unique synergism with LWRs, that offers the potential of fuel recycling having a high degree of proliferation resistance, using simpler and potentially cheaper technologies than conventional reprocessing. High neutron economy also means that about double the thermal energy can be derived from burning fissile material in a CANDU reactor compared to a PWR, regardless of whether the fuel is enriched uranium, MOX, or recycled uranium (RU). High neutron economy also results in high conversion ratios, that can approach unity with the self-sufficient equilibrium thorium cycle (meaning that as much fissile material is produced as is consumed).

Most CANDU reactors have failed-fuel detection systems; on-power refuelling enables prompt removal of any failed fuel. This reduces the risk to a utility of introducing a new fuel type. An extensive array of in-core flux detectors has always been a feature of CANDU reactors, and this ensures that the flux and power distributions are well known, regardless of the fuel type and fuel-management strategy.

Finally, the basic CANDU fuel bundle design lends itself to fuel-cycle flexibility. The fuel composition can be easily varied from ring to ring. Again, with the channel design and separation of channels from each other with large volumes of heavy water, there is a sameness in the neutron spectrum entering the fuel lattice, regardless of the details of the fuel design. Hence, new fuels can be accommodated within operating reactors without changes to the fuel bundle geometry.

3. NATURAL URANIUM FUEL IN CANDU REACTORS

In considering the CANDU fuel-cycle vision, it is important to understand the benefits derived from the use of natural uranium fuel to appreciate why it remains such an attractive option for CANDU owners.

The CANDU fuel bundle is relatively small (0.5 m in length, 10 cm in diameter), and easily handled (about 20 kg). It consists of only 7 distinct components (pellets, sheath, CANLUB coating inside the sheath, spacer pads, bearing pads, end-plugs and end-plates). Hence, it is an easily manufactured product that client countries have found straightforward to localize. The use of natural uranium fuel itself simplifies manufacture, handling, as well as sourcing and diversity of fuel supply.

The uranium requirements (mined uranium required per unit of electricity generated) are about 30% lower than for a PWR reactor. The use of natural uranium generates no depleted-uranium enrichment plant tails waste – in total, a more environmentally friendly front-end of the fuel cycle.

A consequence of these factors is that fuelling costs in CANDU reactors (per unit of electricity generated) are a factor of 2 lower than for PWRs [2].

After 350 reactor-years of operation, the failure rate of CANDU fuel is very low - less than 0.1% bundle failure rate. The ability to locate the infrequent defects that do occur, and to remove the failed fuel during normal on-power refuelling operations, minimizes coolant system contamination, and the economic effect of fuel defects. Reactivity mechanisms are not part of the fuel bundle assembly, again simplifying fuel manufacture, and facilitating good fuel performance. Any dissolved neutron absorber that might be used for reactivity control is confined to the moderator, precluding the possibility of precipitation onto the fuel from the coolant, and the problems that have occurred with other reactors recently.

Nor is the lower CANDU fuel burnup a disadvantage in the back-end of the fuel cycle [3]. An extensive assessment of the Canadian concept for geological disposal has just been completed, which has confirmed its technical soundness [4]. The concept is based on deep geological disposal in an underground vault located in plutonic rock. The density of fuel emplacement in such a facility is determined primarily by the heat load of the spent fuel. The higher quantity of spent natural uranium CANDU fuel, compared to higher burnup PWR fuel, is offset by its lower heat load. The simplicity and small size and weight of the CANDU bundle also reduces the cost of the emplacement system. The overall disposal cost per unit of electricity produced is similar for spent natural uranium CANDU fuel and spent PWR fuel. This is borne out in the OECD/NEA assessment of disposal costs [5]. Also, the size of the repository is small, considering the electricity produced.

Given all of these benefits then, any new fuel or fuel cycle will need to offer compelling advantages before it is introduced. The rest of this paper will identify some of these advantages.

4. THE CANFLEX FUEL BUNDLE

Despite the outstanding performance of existing fuel designs, the first "compelling" product that will be introduced, at least in Canada, is the new CANFLEX fuel bundle, fuelled initially with natural uranium fuel. The CANFLEX fuel bundle has been developed by AECL since 1986, and jointly with the Korea Atomic Energy Research Institute (KAERI) since 1991 [6, 7]. It is now near commercial implementation. In 1998, a demonstration irradiation of 24 bundles will be initiated in the Point Lepreau power reactor in New Brunswick, Canada. A full-scale critical heat flux (CHF) test in water will also be completed this year, which will culminate an extensive series of qualification tests and which will establish definitively the improvement in thermalhydraulic margin over the 37-element bundle.

CANFLEX is a 43-element bundle, with 2 element sizes. The increased number of elements, and element size-grading will reduce peak linear element ratings by 20% compared with those of the 37-element bundle, with performance and safety benefits. This improvement applies to natural uranium, as well as to a variety of enriched fuels and burnups. Patented CHF-enhancing appendages provide the improvement in thermalhydraulic performance.

What will make the initial introduction of CANFLEX a "compelling" product is its application in plant-life management, by maintaining thermalhydraulic performance in the face of various aging phenomena.

5. SEU IN CANDU REACTORS

In many countries, including Canada and Korea, we would anticipate that after the introduction of CANFLEX bundles containing natural uranium fuel, the next step in the evolution of CANDU fuel cycles would be the introduction of SEU fuel, using the CANFLEX bundle as the carrier. The 20% lower linear element ratings in CANFLEX reduce the peak operating temperatures and hence, fission-gas release, facilitating the achievement of higher burnups. Moreover, the increased thermalhydraulic margins obtained with CANFLEX fuel provide a significant performance enhancement in addition to the other benefits of enrichment.

The inherent differences in the neutronics, and the low fabrication cost of CANDU fuel, mean that the optimal enrichment that minimizes the fuel cycle cost in CANDU reactors is much lower than in a PWR: between 0.9% and 1.2%, with most of the benefits already achieved between 0.9% and 1.0%. This lower enrichment (and burnup) avoids the life-limiting phenomena that must be addressed in high-burnup LWR fuel. Enrichments around 0.9% are below the threshold at which criticality considerations result in restrictions and complications in fuel fabrication and fuel handling. Moreover, with this level of enrichment, fuel management is extremely simple: a regular 2- or 4-bundle shift, bi-directional fuelling scheme results in excellent axial power distributions, with or without the presence of the adjuster rods. Another paper in this conference summarizes the results of time-dependent fuel management simulations [8]. It is also anticipated, that at these enrichments, the transition from a natural uranium-fuelled core to an SEU-fuelled core can be achieved in a straightforward fashion, by simply replacing natural uranium fuel with SEU during the normal course of refuelling. Operational considerations are easily met with enrichment at this level, with no changes to the reactor.

Enrichments between 0.9% and 1.2% would reduce fuel-cycle costs by 20 to 30%. This cost savings is partly due to an improvement in uranium utilization: natural uranium requirements (per unit of electricity generated) are reduced by about 25% compared to natural uranium fuel in CANDU reactors. Moreover, with enrichments in this range, spent fuel disposal costs are reduced relative to natural uranium by as much as 30% [9].

In reactors that have surplus heat removal capability, or in which this can be provided in a cost-effective manner during a planned outage, SEU can be used to uprate the reactor power without increasing the limits on maximum bundle or channel power, by flattening the channel power distribution across the core. This power uprating is done by increasing the power in the outer channels (by reducing their burnup through increasing their refuelling rate). Fuel burnup is hence traded-off against higher core power. Power uprating can provide a large economic benefit to operating plants.

In new reactors, SEU provides greater flexibility in design. Using power flattening to obtain more power from a given-sized core has an advantage in capital costs over simply adding more channels to the reactor. In the SEU-fuelled CANDU 9 reactor, using enrichment of around 0.9% to flatten the channel power distribution in the core results in ~1100 MW(e) from a 480-channel, Darlington-size core, nominally rated at 935 MW(e). SEU could also be used to increase the pressure-tube thickness to extend pressure tube lifetime, or to upgrade the primary-heat-transport system (PHTS) conditions, thereby achieving higher thermodynamic efficiency. The moderator inventory could be reduced by decreasing the moderator and reflector volumes. SEU also offers greater flexibility in fuel-bundle design, providing, for example, a means of tailoring reactivity coefficients.

Finally, the use of RU from reprocessed spent LWR fuel offers access to a potentially very economical supply of enrichment at the optimal enrichment level. Previous studies with COGEMA confirmed the suitability of this material as feedstock for CANDU fuel pellets. An earlier preliminary assessment identified the potential advantages of this material in CANDU reactors, especially compared to re-enrichment in a PWR [10]. A detailed assessment of the use of RU in CANDU reactors is currently underway as part of a collaborative program between AECL, BNFL, and KAERI. If this assessment confirms the business case for RU, then the next step will be a demonstration irradiation in a power reactor with CANFLEX fuel. In this context, RU is considered to be available on the open market, and is not linked to a utility's decision to reprocess. Other papers in this conference provide further details on the use of CANFLEX with RU [11,12].

6. RECYCLE OF SELF-GENERATED PLUTONIUM

Resource and economic considerations are prime drivers in decisions on recycling. The availability and cost of fissile material (starting with natural uranium), the cost of processing (enrichment), the cost of fissile material recovery (reprocessing) and the cost of fuel fabrication are all determinants in the decision to recycle.

If one considers spent fuel as a mine of fissile material, then the spent natural uranium CANDU ore is dilute. The ^{235}U concentration in the spent fuel is at the level of depleted-uranium enrichment tails (~0.2%), so there is no economic incentive for its recovery. The fissile plutonium is also dilute, typically 2.6 g fissile Pu/initial kg U. In contrast, in spent PWR fuel, depending on the initial enrichment and discharge burnup, the ^{235}U concentration is around 9 g/initial kg U, while the concentration of fissile Pu is ~ 6 g/initial kg U. Because the cost of recovery is dependent to the concentration of the fissile material (or to the amount of material that has to be processed), then clearly spent PWR fuel will be a cheaper "mine" of fissile material than spent natural uranium CANDU fuel.

Hence, the cost of its recovery does not warrant Pu-recycle from spent natural uranium in the foreseeable future. Nor would waste disposal considerations change this conclusion, as geological disposal of spent CANDU fuel has been shown to be technically and environmentally sound, and the disposal of reprocessing wastes does not have any inherent advantages over the disposal of spent CANDU fuel [3]. Moreover, in the Canadian context, it is important to establish that from any grounds – technical, economic, social, political or environmental – there is a viable and acceptable solution to the permanent disposal of spent fuel. This will most likely require the disposal of at least some of the stockpile of spent CANDU natural uranium fuel to establish public confidence, and to address this major issue in public acceptance with nuclear power.

7. CANDU/PWR SYNERGISM

As was established in the previous section, spent PWR (LWR) fuel has a higher fissile concentration than spent natural uranium CANDU fuel. CANDU is the best reactor in which to recover the energy from the recycled material: because of its good neutron economy, up to double the thermal energy can be extracted from the recycled material, whether uranium or plutonium [13]. Moveover, the high neutron economy, coupled with fuel-cycle flexibility, enable a wide range of options to be envisioned for exploiting this fuel-cycle synergism; some of these options are unique to the CANDU reactor.

At the one end of the spectrum of recycling options is conventional reprocessing, in which the uranium (RU) and plutonium are separated from one another, and from the actinide and fission product waste. We have seen that the use of as-is unenriched RU in CANDU reactors offers many attractions. This option would be complementary to the recycle of the plutonium as MOX fuel in either PWR or CANDU reactors. The economical use of MOX fuel in CANDU reactors would favour higher burnups than are optimal for SEU fuel. (The cost of MOX fuel fabrication will be independent of the amount of plutonium contained; hence, there is an incentive to maximize the MOX burnup and minimize the number of MOX bundles fabricated.) The simple fuel design and short bundle length should be advantageous in remote fabrication. High neutron economy means that roughly double the energy can be recovered from the plutonium by recycling it in CANDU reactors rather than in PWRs.

The third product from reprocessing is the actinide and fission product waste. Nowhere else is the inherent CANDU fuel-cycle flexibility more evident than in its ability to utilize this material in existing reactors [14]. Detailed fuel management simulations have confirmed the ability to use a full core of an actinide-waste/plutonium mixture in existing fuel bundle geometries. Simple fuel management schemes would be employed; refuelling rates are easily within the capability of the current systems; bundle and channel powers are within licensing limits for natural uranium fuel; and with the very high thermal conductivity of the preferred inert-matrix carrier – SiC – fuel operating temperatures are very low, just above coolant temperatures; very low fuel temperatures, and negative void reactivity result in outstanding inherent safety features. The studies, to date, have been done using the unadjusted ratio of minor-actinides-to-plutonium from PWR fuel, and no optimization has been done of the actinide mix. The reference fuel composition has 356 g plutonium, and 44 g minor-actinides (^{237}Np, ^{241}Am, ^{243}Am) in a 37-element bundle. With this mixture, the net destruction efficiency of the total initial actinide inventory is 60%; 90% of the initial fissile plutonium inventory is destroyed. This is a longer-term fuel-cycle option, because development of the inert-matrix fuel is required. If other fuel carriers are found to be superior to SiC, then they could just as easily be used. Another paper in this conference provides an update on AECL's reactor physics and fuel studies on inert-matrix fuels [15].

At the other end of the spectrum is a group of recycling options for which the acronym "DUPIC" has been coined: Direct Use of Spent PWR Fuel In CANDU [16]. These options are unique to CANDU reactors, and exploit the reactor's ability to use fuel with low fissile content. Such is the neutron economy of the CANDU reactor, that the fissile content of the spent PWR fuel can be used as-is, without enhancement. Indeed, even removal of the fission products from spent PWR fuel is not required in order to achieve an appreciable burnup.

One example of direct use would be to simply cut the PWR fuel elements into CANDU length (~50 cm), straighten them, then weld new end-caps to the ends. (Optionally, the elements could be double-clad.) The smaller diameter of PWR elements would enable the use of a 48- or 61-element fuel bundle, which would significantly reduce the linear element ratings compared with those of a 37-element bundle and enhance fuel performance, and would help to accommodate the variation in fissile content between elements. Another option is the OREOX process – a thermal-mechanical process that reduces the used PWR pellets to a powder, after the cladding has been removed. The powder would be pressed and sintered as "new" CANDU pellets, and loaded into standard sheaths that would be assembled into standard bundles. The technical feasibility of this second option is the focus of a collaborative program involving the AECL, KAERI, and the US Department of State [17]. The IAEA also participates in the safeguards aspects of this program. The recent successful fabrication of 3 DUPIC elements from spent PWR fuel, by AECL and KAERI staff, is described in another paper in this conference [18].

These DUPIC recycling options offer advantages over conventional reprocessing. They all use only dry processes: no wet chemistry is involved, and indeed, there are virtually no liquids. They are simpler than conventional reprocessing, and the expectation is that they will be cheaper. While very preliminary economic analysis suggests that this is the case [19], much more technical work will be required to define the processes before more definitive costs can be established.

A major attraction of the DUPIC fuel-cycle options is that they offer a high degree of proliferation resistance. Although no fuel or fuel cycle is proliferation-proof, several features of the DUPIC processes significantly enhance its proliferation resistance:

- The proliferation barriers that are present in spent fuel are also present in the DUPIC fuel
- There is no purposeful separation of isotopes; nor can the processes be easily tampered with to effect such a separation
- The fuel processing does not involve any we chemistry; only dry thermal–mechanical processes are employed
- With no selective separation, the plutonium concentration is dilute, making it much more difficult for the removal of a significant quantity
- All stages of the process, as well as the final DUPIC fuel bundles, are highly radioactive, which would make physical access to the material, and its removal, extremely difficult
- The high radioactivity results in an easily detected "signature" of the material, making removal easy to detect
- All processing and handling must be done in a shielded facility, again making physical entry into the facility, and removal of material extremely difficult; these measures also will result in highly automated processes and the inherent abilities to track and log in-cell operations
- The processing facility is entirely self-contained: spent PWR fuel goes in at one end, and finished DUPIC fuel bundles go out the other; there is no transport of intermediate products
- Transportation of the spent PWR fuel into the DUPIC processing facility, and of DUPIC fuel to the CANDU reactor involves highly radioactive materials

Notwithstanding these inherent, self-protecting attributes of the DUPIC process and final product, safeguards measures would be provided, and built into the design of the DUPIC facility [20, 21].

The DUPIC fuel-cycle options offer the potential of significantly reducing spent fuel quantities in a system of CANDU/PWR reactors. Another paper in this conference identifies the attractions of the DUPIC fuel cycle in the Korean context [17].

A recent study by AECL has identified significant economic benefit in the cost of geological disposal with the DUPIC fuel cycle. The heat load of the spent DUPIC fuel (after it had been irradiated in CANDU reactors), is not much different from the decay heat from the original spent PWR fuel. That means that approximately 50% more energy can be derived from the PWR fuel by burning it as DUPIC fuel in CANDU reactors, with no additional penalty in heat load. Because the density of spent fuel packing in a geological repository is determined by the decay heat, this extra energy is obtained with virtually no increase in disposal cost. As a result, the disposal cost for DUPIC fuel (in mills/kWh) is significantly lower than for either spent PWR or CANDU fuel [9].

Finally, conventional reprocessing and DUPIC define two extremes of a spectrum of PWR spent fuel recycling opportunities with CANDU reactors. Most of the space between these extremes has not even been explored. Depending on the local and international constraints and values, the optimal recycling process might lie between these two extremes. In the TANDEM cycle, the uranium and plutonium from spent PWR fuel would be co-precipitated after removal of other actinides and fission products; this step has a higher degree of proliferation resistance than conventional reprocessing, but not as high as with the DUPIC cycle, since the chemistry could be tampered to separate plutonium. A higher degree of proliferation resistance can be achieved by leaving in the highly radioactive fission products (and removing the rare-earths that affect fuel burnup); this choice would also be a much cheaper process than conventional reprocessing, with its very high decontamination factor. Looking at the OREOX process, fuel-cycle economics could be improved by selectively removing the neutron absorbing rare-earth fission products, and hence increasing the burnup of the DUPIC fuel. Several techniques could be envisioned for achieving this.

The CANDU vision is one of an evolutionary reactor, offering a custom fuel cycle to fit local requirements. Fuel-cycle flexibility and high neutron economy open the door to unique recycling opportunities having the potential of significant cost and non-proliferation benefits. Our vision is that the CANDU reactor is an indispensable part of any LWR system employing recycling, on either a national or regional basis. Moreover, our vision is that new recycling technologies will be developed to take purposeful advantage of the unique niche that the CANDU reactor can fill in spent PWR fuel recycle using processes that are simpler and cheaper than reprocessing, and designed from the start with a high degree of proliferation-resistance. The development of such technologies will require international collaboration.

8. CANDU MOX FOR PLUTONIUM DISPOSITIONING

The use of reactors for burning ex-weapons plutonium as mixed-oxide (MOX) fuel converts the plutonium to a form that provides the same proliferation barriers as in spent fuel, while deriving societal benefit through the production of electricity. The use of Canadian reactors, either on their own, or to complement MOX fuel in Russian and US reactors provides an attractive, symmetrical, simultaneous drawdown of ex-weapons plutonium in those countries. The CANDU MOX option is another compelling illustration of fuel cycle flexibility, both in the inherent features of the CANDU reactor, and in the ability to tailor the fuel design to meet specific objectives [14].

The fuel for this application would be either the current 37-element bundle for a burnup of around 10 MWd/kg HE, or the CANFLEX geometry for burnups of 17 MWd/kg HE or higher. The detailed fuel design would depend on the specific objectives of the mission, and would represent a balance between the plutonium disposition rate (e.g., the speed at which the plutonium is converted to spent fuel), the energy derived from the plutonium, the net plutonium destruction efficiency (because plutonium is produced, as well as destroyed, in-reactor), and the MOX fuel fabrication capacity required for the disposition of a given amount of plutonium. The objectives are quite different from that of conventional MOX fuel using plutonium recovered from reprocessing spent PWR fuel, in which maximization of energy recovery and burnup are the major objectives. For this application, depleted uranium is used as the matrix material throughout the bundle. In the central element, and in next ring of fuel (either 6 or 7 elements, depending on whether the bundle is 37-element or CANFLEX), dysprosium is mixed with the depleted uranium (a neutron absorber is not added to the Pu-containing elements, unlike other reactors). The addition of a neutron absorber has three effects: it increases the amount of plutonium required to achieve a given burnup (and hence increases the plutonium disposition rate at the expense of the efficiency of energy production from the plutonium); it reduces the refuelling ripple (the short-term increase in local power during refuelling); and it reduces void reactivity. In all of the fuel designs considered, void reactivity is negative, which, while not necessary, simplifies the safety and licensing analysis by eliminating any power pulse in a loss-of-coolant accident (LOCA). The plutonium is confined to the outer two rings of the bundle, the concentration ranging from 1% to 5%, depending on the burnup.

Fuel and reactor performance for all designs considered is within the current operating and safety envelopes for natural uranium fuel. Fuel management is particularly simple: conventional bi-directional, 2-bundle shifts. A full MOX core can be accommodated with no changes to the reactor (although safe and secure storage of the fresh MOX fuel would have to be provided). The plutonium disposition rate can be increased by increasing the concentration of dysprosium or by downgrading slightly the purity of the coolant and moderator. Two of the four 825 MW(e) reactors at the Bruce A station near Kincardine, Ontario, could disposition 50 te ex-weapons plutonium in 15 to 25 years, depending on the fuel design.

The CANDU MOX option would provide the participation of a trusted third country, Canada, that can provide security and safeguards assurances in a balanced, simultaneous drawdown of both US and Russian ex-weapons plutonium. CANDU MOX is a low-cost, low-risk option, readily available in the near term, which would enable a quick start to the disposition of ex-weapons plutonium. Another paper in this conference describes a collaborative program between Canada, the United States and Russia aimed at qualifying CANDU MOX fuel for this purpose [22].

9. MOX FUEL EXPERIENCE IN CANDU REACTORS

AECL has more than 30 years of experience in research and development on Pu-containing MOX fuels [23]. Research activities include development of MOX fuel fabrication technology, measurement of physical properties, production of prototype fuel, experimental irradiations and post-irradiation examinations (PIE), and reactor physics measurements in the zero-power ZED-2 reactor.

The Recycle Fuel Fabrication Laboratory (RFFL) at the Chalk River Laboratories is designed to produce experimental quantities of MOX for reactor physics tests or demonstration irradiations. Following an extensive commissioning campaign using natural UO_2, a number of MOX fuel fabrication campaigns were completed in the RFFL from 1979 to 1987, producing various quantities of fuel with different compositions. After a stand-by period of about 8 years, a project to rehabilitate the RFFL and bring it back into production was completed in June 1996. MOX operations were resumed in the facility with the production of thirty-seven 37-element $(U,Pu)O_2$ bundles destined for void reactivity measurements. This campaign was completed in March 1997 [24].

Fuel performance with CANDU MOX fuel has been found to be generally equivalent to that of UO_2. Another paper in this conference describes a recent post-irradiation examination (PIE) of 4 MOX fuel bundles irradiated at high power in the NRU research reactor to a range of burnups [25].

10. THORIUM FUEL CYCLES IN CANDU REACTORS

There are several characteristics of thorium fuel and fuel cycles that make them of interest in the overall CANDU fuel-cycle vision [26]. The primary driving force is the long-term extension of nuclear fuel resources. The abundance of thorium in the earth's crust is about 3 times that of uranium. Although thorium does not contain a fissile component, ^{233}U is produced in-reactor through neutron capture in ^{232}Th, and subsequent beta-decay of ^{233}Th and ^{233}Pa. The concentration of ^{233}U in the spent fuel is about 5 times that of ^{239}Pu in spent natural uranium UO_2 fuel. This isotope of uranium is a very valuable fissile material because of the high number of neutrons produced per neutron absorbed (η) in a thermal neutron spectrum. Recycling the ^{233}U can reduce mined uranium requirements by up to 90% [27]. Complete independence from uranium is theoretically possible with the self-sufficient thorium fuel cycle, which in equilibrium, produces as much ^{233}U as is consumed. Hence, a single reactor technology can provide both short-term and long-term assurance of fuel supply. Alternatively, high conversion-ratio CANDU reactors utilizing thorium would be synergistic with more expensive, fast-breeder reactors (FBRs), supplying the initial fissile material. Also, because commercial thorium fuel recycling facilities have not been built, there is an opportunity to develop a new, proliferation-resistant technology for recycling.

While the full exploitation of the energy potential of thorium requires recycling, which will not be economically justified for many years, the allure of using thorium in CANDU reactors is that benefit can be derived from this fuel today, in existing reactors, at fuel-cycle costs that are comparable with the already low cost of natural uranium fuelling; and with improved uranium utilization compared to natural uranium fuel. A strategic mine of ^{233}U can be produced that is safeguarded in the spent fuel, and available for future recovery and recycle when predicated by economic, technical, and strategic considerations. This possibility will be of particular interest in those countries having abundant thorium reserves, but lacking in uranium.

This bridge between the thorium recycle options of the future, and current uranium-based fuel cycles is the once-through thorium (OTT) cycle in CANDU reactors. Our analysis indicates that the optimal OTT cycle is economical today, both in terms of money and in terms of uranium resources. Two general approaches have been devised for OTT cycles in CANDU reactors. The first is a "mixed-core" approach, in which a large number of channels fuelled with "driver" fuel would provide the external source of neutrons for a fewer number of channels fuelled with ThO_2. This is the conventional OTT, and theoretically, values of enrichments, burnups, and relative feed rates can be chosen that make this fuel cycle competitive (both in terms of resource utilization and in economics) compared not only with natural uranium, but also with SEU fuel [28, 29]. On-power refuelling enables the ThO_2 fuel to remain in the core much longer than the driver fuel. With the large disparity between the properties of the "driver" fuel and the ThO_2 channels, fuel management would be particularly challenging.

A "mixed-fuel bundle" approach is an alternative strategy that has recently been devised by AECL, which provides a practical means of utilizing thorium in operating CANDU reactors. Although the uranium utilization is not quite as good as in the "mixed-core" approach, this strategy has many benefits: uranium resource utilization is better than with natural uranium fuel, and fuel-cycle costs are comparable; fuel management is particularly simple; refuelling rates (in bundles per day) are a third of those with natural uranium; excellent axial power distributions are obtained, with or without adjuster rods; maximum bundle and channel powers are lower than with natural uranium fuel; and void reactivity is reduced. The "mixed-fuel bundle" contains ThO_2 in the central 8 elements of a CANFLEX bundle, and SEU in the outer 2 rings of elements. The disadvantage compared to the "mixed-core" approach is that separate dwell times cannot be achieved for the ThO_2 and the driver fuel because they are part of the same bundle. However, even with a modest bundle-average burnup of about 22 MWd/kg HE, the ThO_2 elements experience sufficient irradiation that they contribute positively to the overall uranium utilization. (While the overall uranium utilization is better than for natural uranium fuel, it is not quite as good as for SEU alone.) Details of these OTT fuel management studies are published for the first time in another paper in this conference [30].

Although the primary focus for interest in thorium fuel cycles in CANDU reactors is uranium resource extension, there are other benefits. The thermal conductivity of ThO_2 (thoria) is about 50% higher than that of UO_2 over a large temperature range, and its melting temperature is 340°C higher than that of UO_2 [31, 32]. As a consequence, fuel operating temperatures will be lower, and all thermally activated processes, such as creep and fission gas diffusion will be reduced. Fission-gas release from ThO_2 fabricated with proper control of microstructure will be lower than for UO_2 operating under similar ratings. Thoria is chemically very stable and does not oxidize, a benefit for normal operation, postulated accidents, and waste management – both interim storage, and for geological disposal [33].

Thorium-232 produces fewer minor actinides than does ^{238}U. The resultant lower radiotoxicity of spent thorium fuel is sometimes claimed to be a benefit in waste management. However, in the Canadian concept for engineered geological disposal, the actinides contained in used fuel are not a significant contributor to radiological risk [34, 35], and this benefit is judged to be small.

In AECL's fuel-cycle vision, thorium fuel cycles ensure long-term nuclear fuel supply using a single reactor type. In general, such cycles would not be employed until shortages of uranium resulted in significant increases in uranium price. Countries with abundant thorium reserves may elect to deploy the OTT fuel cycle earlier in CANDU reactors, to acquire experience in thorium fuel-cycle technology, and to build a strategic resource of ^{233}U safeguarded in the spent fuel, without committing to its future recovery. This would provide a low-cost insurance policy against future shortages of uranium.

11. DEVELOPMENT REQUIREMENTS FOR FUTURE FUEL CYCLES

Finally, underpinning these specific fuel-cycle developments are generic advancements in fuel design and performance that can be applied to any of these advanced fuels, including SEU, MOX or thorium. These include a generic high-burnup element design, an advanced CANLUB coating, enhanced thermalhydraulic performance, tailored reactivity coefficients, and low-temperature fuels (such as inert-matrix, or graphite-disk fuel). As well, advanced characterization techniques will help to elucidate the relationship between fuel properties and fuel performance for advanced fuels. Innovative techniques currently under development in AECL include the use of advanced techniques for measuring the diffusion coefficient of fission gases [36], and methods to accurately determine plutonium distribution in MOX fuel.

12. SUMMARY: CANDU FUEL-CYCLE VISION

No single fuel-cycle path is appropriate for all countries. Many local and global factors will affect the best strategy for an individual country. Fuel-cycle flexibility is an important factor in an ever-changing, and unpredictable world. CANDU is an evolutionary reactor, offering a custom fuel cycle to fit local requirements. Its unsurpassed fuel-cycle flexibility can accommodate the widest range of fuel-cycle options in existing CANDU stations.

In the near-term, CANFLEX bundles will be deployed with natural uranium fuel, to benefit from its enhanced thermalhydraulic performance. The use of SEU in CANFLEX bundles would be the next logical step. If the business case confirms the compelling benefits of RU, then that will be the preferred source of enrichment.

Our vision is that the CANDU reactor will be an indispensable part of any LWR system employing recycling, on either a national or regional basis. Initially, that synergism may be based on conventional reprocessing, with RU, and perhaps MOX, being recycled in CANDU reactors. Some countries will see RU-use in CANDU reactors, and eventually actinide-burning as complementary to MOX fuel in their PWRs. In some regions, there will be a strong incentive to develop advanced recycling technologies, such as DUPIC, that can take purposeful advantage of the CANDU niche in recycling spent PWR fuel using processes that are simpler and cheaper than conventional reprocessing and that are designed from the start with a high degree of proliferation resistance. The development of such technologies will require international collaboration, and international organizations, such as the IAEA, can play a role in their development.

The OTT cycle will be employed first by countries having extensive thorium reserves, but lacking indigenous uranium. Only when uranium prices are very high will thorium fuel cycles involving ^{233}U recycle be introduced. In the long term, the CANDU reactor is synergistic FBRs, with a few expensive FBRs supplying the fissile requirements of cheaper, high conversion-ratio CANDU reactors, operating on the thorium cycle.

REFERENCES

[1] IAEA International Symposium, "Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities", Vienna, Austria, 1997 June 3-6, IAEA-SM-346.

[2] OECD/NEA, "The Economics of the Nuclear fuel Cycle", Paris (1994).

[3] ALLAN, C.J., BAUMGARTNER, P., "Back-End of the Nuclear Fuel Cycle: A Comparison of The Direct Disposal and Reprocessing Options", Proc. Global '97, Yokohama, Japan, 1997 Oct. 5-10.

[4] Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel. 1998. Nuclear Fuel Waste Management and Disposal Concept. Canadian Environmental Assessment Agency, 13th Floor, Fontaine Bldg., 200 Sacre-Coeur Blvd., Hull, Quebec, K1A 0H3.

[5] OECD/NEA, "The Cost of High-Level Waste Disposal in Geological Repositories. An Analysis of Factors Affecting Cost Estimates", Paris (1993).

[6] SUK, H.C., SIM, K-S., KIM, B.G., CHOI, C.B., CHUNG, C.H., LANE, A.D., SEARS, D.F., LAU, J.H.K., OLDAKER, I., BOCZAR, P.G., "CANFLEX as a CANDU Advanced Fuel Bundle", Proc. 5th Intl. Topical Mtg. on Nuclear Thermal Hydraulics, Operations and Safety, 1997 April 14-18, Beijing, China.

[7] INCH, W.W.R., THOMPSON, P., SUK, H.C., "CANFLEX: From Development Concept to a Proven Fuel", KAIF/KNS Annual Conf., Seoul, Korea, 1998 April 15-16.

[8] DONNELLY, J.V., D'ANTONIO, M., "Fuel-Management Simulations for 0.9% SEU in CANDU 6", these Proceedings.

[9] BAUMGARTNER, P., ATES, Y., BOCZAR, P.G., ELLIS, R., JOHNSON, L., "Disposal Costs for Advanced CANDU Fuel Cycles", Proc. 11th PBNC, Banff, Canada, 1998 May 3-7.

[10] BOCZAR, P.G., SULLIVAN, J.D., HAMILTON, H., TOWNES, B.M., LEE, Y.O., JEONG, C.J., SUK, H.C., MUGNIER, C., "Recovered Uranium in CANDU: A Strategic Opportunity", Proc. International Nuclear Congress and Exhibition, Toronto, Canada, 1993 October 3-6.

[11] WASH, M.R., INCH, W.W.R., PAGE, R.J., MARSH, G., "Recycled Uranium - An Advanced Fuel for CANDU Reactors", these Proceedings.

[12] SUK, H.C., SIM, K-S, KIM, B.G., "CANFLEX-RU Fuel Development Program as One Option of Advanced Fuel Cycles in Korea", these Proceedings.

[13] BOCZAR, P.G., FEHRENBACH, P.J., MENELEY, D.A., "CANDU Fuel Cycle Options in Korea", KAIF/KNS Annual Conf., Seoul, Korea, 1996 April 11-12; also Atomic Energy of Canada Limited Report AECL-11586 (1996).

[14] CHAN, P.S.W., GAGNON, M.J.N., BOCZAR, P.G., ELLIS, R.J., VERRALL, R.A., "CANDU - A Versatile Reactor for Plutonium Disposition or Actinide Burning", Proc. Global '97, Yokohama, Japan, 1997, Oct. 5-10.

[15] VERRALL, R.A., ANDREWS, H.R., CHAN, P.S.W., GEORGE, I.M., HAYWARD, P.J., LUCUTA, P.G., SUNDER, S., VLAJIC, M.D., KRSTIC, V.D., "CANDU Inert-Matrix Fuel", these Proceedings.

[16] KEIL, H., BOCZAR, P.G., PARK, H.S., “Options for the Direct Use of Spent PWR Fuel in CANDU (DUPIC)”, Proc. 3rd Intl. Conf. on CANDU Fuel, Chalk River, Canada, 1992 Oct. 4-8.

[17] LEE, J.S., YANG, M.S., PARK, H.S., SULLIVAN, J.D., BOCZAR, P.G., GADSBY, R.D., “The DUPIC Fuel Cycle Synergism between LWR and HWR”, these Proceedings.

[18] SULLIVAN, J.D., RYZ, M.A., LEE, J.W., “Fabrication of CANDU DUPIC Fuel”, these Proceedings.

[19] CHOI, J.W., KO, W.N., LEE, J.S., JUNG, I.H., PARK, H.S., “Preliminary Conceptual Design and Cost Analysis of the DUPIC Fuel Fabrication Plant”, Proc. Korean Nuclear Society Spring Meeting, Cheju, Korea, 1996 May.

[20] HONG, J.S., KIM, H.D., LEE, Y.G., PARK, H.S., PUCKETT, J., THOMAS, K., MENLOVE, H., RINARD, P., COULTER, A., BURR, T., “Safeguards Initiatives for the Direct Use of Spent PWR Fuel in CANDU Reactors (DUPIC) Process”, 37th INMM, Naples, Florida, USA, 1996 July.

[21] LEE, Y.G., CHA, H.R., HONG, J.S., MENLOVE, H., RINARD, P., “Development of DUPIC Safeguards Neutron Counter”, 38th INMM, Phoenix, USA, 1998 July.

[22] COX, D.S., GADSBY, R.D., CHAN, P.S.W., DIMAYUGA, F.C., “Disposition of Excess-Weapons Plutonium as MOX Fuel in CANDU Reactors”, these Proceedings.

[23] DIMAYUGA, F.C., “AECL’s Experience in MOX Fuel Fabrication and Irradiation”, Proc. IAEA Technical Committee Meeting, Recycling of Plutonium and Uranium in Water Reactor Fuels, Windermere, U.K., 1995 July 3-7.

[24] DIMAYUGA, F.C., “Fabrication of Simulated Mid-Burnup CANDU Fuel in the RFFL”, Proc. 5th Intl. Conf. on CANDU Fuel, Toronto, Canada, 1997 Sept. 21-24.

[25] FLOYD, M.R., ZHOU, Y.N., RYZ, M.A., DIMAYUGA, F.C., “Performance Testing of CANDU MOX Fuel”, these Proceedings; also Atomic Energy of Canada Limited Report AECL-11932 (1998).

[26] BOCZAR, P.G., CHAN, P.S.W., ELLIS, R.J., DYCK, G.R., SULLIVAN, J.D., TAYLOR, P., JONES, R.T., “A Fresh Look at Thorium Fuel Cycles in CANDU Reactors”, Proc. 11th PBNC, Banff, Canada, 1998 May 3-7.

[27] VEEDER, J., DIDSBURY, R., “A Catalogue of Advanced Fuel Cycles in CANDU-PHW Reactors”, Atomic Energy of Canada Limited Report AECL-8641 (1985).

[28] MILGRAM, M.S., “Once Through Thorium Cycles in CANDU Reactors”, Atomic Energy of Canada Limited Report AECL-7516 (1982).

[29] DASTUR, A.R., MENELEY, D.A., BUSS, D.B., “Thorium Cycle Options in CANDU Reactors”, Proc. Global 95, Versailles, France, 1995.

[30] CHAN, P.S.W., BOCZAR, P.G., ELLIS, R.J., ARDESHIRI, F., “Fuel-Management Simulations for Once-Through Thorium Fuel Cycle in CANDU Reactors”, these Proceedings.

[31] BELLE, J., BERMAN, R.M., “The High-temperature Ex-reactor Thermal Conductivity of Thoria and Thoria-urania Solid Solutions (LWBR/AWBA Development Program)”, Report WAPD-TM-1530 (1982).

[32] FINK, J.M., CHASANOV, M.G., LEIBOWITZ, L., "Thermal Conductivity and Thermal Diffusivity of Solid UO_2", Report, ANL-CEN-RSD-81-3 (1981).

[33] TAYLOR, P., HOCKING, W.H., JOHNSON, L.H., MCEACHERN, R.J., SUNDER, S., "A Comparison of $(Th,Pu)O_2$ and UO_2 Fuels as Waste Forms for Direct Disposal", Nuclear Technology. Vol. 116, pp. 222-230 (1996).

[34] GOODWIN, B.W., MCCONNELL, D.B., ANDRES, T.H., HAJAS, W.C., LENEVEU, D.M., MELNYK, T.W., SHERMAN, G.R., STEPHENS, M.E., SZEKELY, J.G., BERA, P.C., COSGROVE, C.M., DOUGAN, K.D., KEELING, S.B., KITSON, C.I., KUMMEN, B.C., OLIVE, S.E., WITZKE, K., WOJCIECHOWSKI, L., WIKJORD, A.G., "The Disposal of Canada's Nuclear Fuel Waste: Postclosure Assessment of a Reference System", Atomic Energy of Canada Limited Report AECL-10717 (1994).

[35] WIKJORD, A.G., BAUMGARTNER, P., JOHNSON, L.H., STANCHELL, F.W., ZACH, R., GOODWIN, B.W., "The Disposal of Canada's Nuclear Fuel Waste; A Study of Postclosure Safety of In-Room Emplacement of Used CANDU Fuel in Copper Containers in Permeable Plutonic Rock; Volume 1: Summary" Atomic Energy of Canada Limited Report, AECL-11494-1, COG-95-552-1 (1996)

[36] HOCKING, W.H., VERRALL, R.A., BUSHBY, S.J., "A New Technique To Measure Fission-Product Diffusion Coefficients in UO_2 Fuel", these Proceedings.