FUTURE FUEL CYCLE DEVELOPMENT FOR CANDU REACTORS

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ABSTRACT

The CANDU reactor has proven to be safe and economical and has demonstrated outstanding performance with natural uranium fuel.[a] The use of on-power fuelling, coupled with excellent neutron economy, leads to a very flexible reactor system which can utilize a wide variety of fuels. The spectrum of fuel cycles ranges from natural uranium, through slightly enriched uranium, to plutonium and ultimately thorium fuels which offer many of the advantages of the fast breeder reactor system. CANDU can also burn the recycled uranium and/or the plutonium from fuel discharged from light water reactors. This synergistic relationship could obviate the need to re-enrich the reprocessed uranium and allow a simpler reprocessing scheme. Fuel management strategies that will permit future fuel cycles to be used in existing CANDU reactors have been identified. Evolutionary design changes will lead to an even greater flexibility, which will guarantee the continued success of the CANDU system.

INTRODUCTION

The performance of CANDU reactors has been outstanding. CANDU reactors have consistently ranked among the best in the world in performance. These include not only the multi-unit stations operated by the provincial utility Ontario Hydro, but also single units operated by other utilities, such as those in New Brunswick and Quebec, and in other countries, such as Korea and Argentina. This performance is due, at least in part, to the discipline imposed by the choice of heavy water as moderator and coolant and natural uranium as fuel.

The choice of natural uranium and heavy water led to the pressure-tube design with on-power fuelling. On-power fuelling is used to control the reactivity change due to fuel burnup, without recourse to reactivity suppression methods, such as burnable poisons. This feature contributes about 6% to overall reactor availability. The use of heavy water and structural materials with low neutron absorption results in a reactor with excellent neutron economy and thus the most efficient uranium utilization of current commercial reactor types. The short, simple CANDU fuel bundles, in conjunction with on-power fuelling, have resulted in low fuelling costs and very low fuel-failure rates. Further, the relatively high cost of heavy water has led to the development of pumps, valves and boilers of high reliability. These factors all contribute to the superior operational performance of the CANDU system.

The emphasis on neutron economy and the use of on-power fuelling also result in a reactor that can accommodate a variety of different fuels and fuel cycles without significant changes to the basic design. Fuel cycles using natural uranium, enriched uranium, recycled uranium and/or plutonium from light water reactors (LWRs), and ultimately thorium, with its potential for a U-233 breeding cycle, are some of the possible fuelling options.

ECONOMIC AND URANIUM RESOURCE CONSIDERATIONS

The growth in installed nuclear power has fallen short of that predicted a decade ago. As a result, the existing worldwide uranium production capability should exceed requirements until about 1990. Following this period the development of new uranium production facilities will be required.[1] A number of rich uranium deposits in Australia and Canada have been identified in recent years and are expected to be developed. No overall imbalance in supply and demand is expected, although local imbalances already exist and are expected to continue. Consequently, the driving force to introduce advanced fuel cycles has changed from resource utilization to economics. In some countries, strategic or political considerations may spur the development of

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[a] CANDU is an acronym for CANada Deuterium-Uranium. CANDU is a registered trademark of Atomic Energy of Canada Limited.

advanced fuel cycles, and increase the interest in more efficient uranium utilization, e.g. the goal of energy self-sufficiency, the problem of storing increasing amounts of spent fuel, or a desire to obtain energy from the plutonium in spent fuel.

Among the commercially available reactor systems, CANDU fuelled with natural uranium has the most efficient resource utilization.[2] Advanced fuel cycles in CANDU offer the possibility of even greater resource conservation. Figure 1 compares the annual equilibrium natural uranium (NU) requirements for pressurized water reactors (PWRs) and CANDUs operating on various fuel cycles.

The reference once-through PWR system has a burnup of about 33 000 MWd/t, with 3.3% uranium enrichment. Improvements in existing PWRs have the potential for reducing annual uranium requirements by about 20%, while improvements in future PWRs could reduce uranium requirements by as much as 33%.[3] Recycling of plutonium and uranium in existing PWRs has the potential for reducing annual uranium requirements by as much as 48% [4] which is about the same saving as would be achieved by recycling plutonium in a PWR with a tight lattice pitch.[5]

The implementation of advanced fuel cycles in CANDU reactors would enable CANDU to maintain its superiority in uranium utilization over LWRs.[6] The annual equilibrium uranium requirements for the natural uranium-fuelled CANDU are about 12% lower than for the PWR.

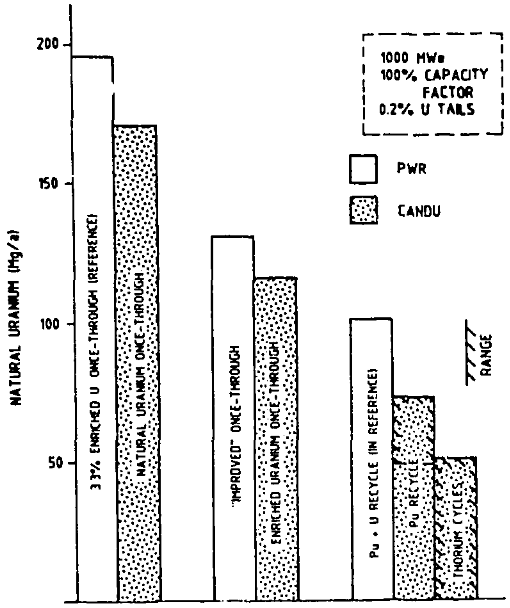


Fig. 1 CANDU and PWR Equilibrium Annual Uranium Requirements

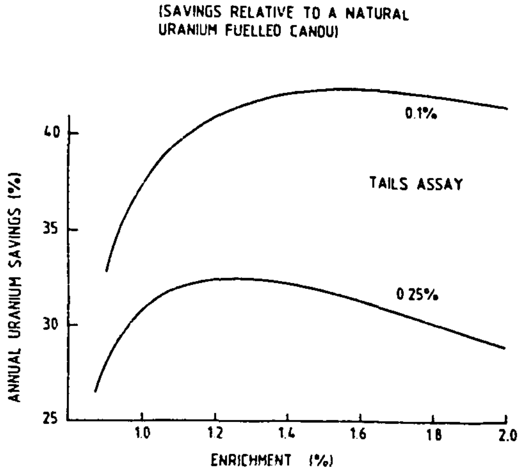


Fig. 2 Annual Natural Uranium Savings with SEU Fuel

Using uranium enrichment in CANDU would maintain this advantage over future improved PWRs. Recycling plutonium in CANDU would further reduce annual uranium requirements by 40 to 50%. Use of the thorium fuel cycle in CANDU promises further significant reductions in annual uranium consumption. The range in uranium requirements shown in Figure 1 for plutonium recycle in CANDU corresponds to different burnups. For thorium cycles, the range corresponds not only to different burnups, but also to different fissile contents. The high end of the range represents 20% enriched uranium content ("denatured" thorium cycle), giving a burnup of 30 000 MWd/t, and the lower end the self-sufficient equilibrium thorium cycle.

It should be noted that annual natural uranium requirement is the most important factor affecting the uranium required to produce a unit of energy, or "the uranium utilization". Other important factors are the uranium required for the initial reactor charge, and any energy derived from additional fissile topping material prior to fuel recycle. The initial natural uranium charge for a PWR is four to five times larger than that for a CANDU reactor of the same electrical output.

The slightly enriched uranium (SEU) fuel cycle in CANDU would use uranium enriched to about 1%.[6] Natural uranium requirements in CANDU are not strongly dependent on enrichment levels between 1 and 2% (see Figure 2). Hence SEU fuel would provide flexibility in the level of enrichment. The SEU cycle would reduce annual consumption of natural uranium by 30% to 40% relative to once-through natural uranium fuelling, depending on the tails assay. The new uranium enrichment methods (such as AVLIS) offer an economical reduction in the optimal tails assay with a resultant improvement in uranium utilization.

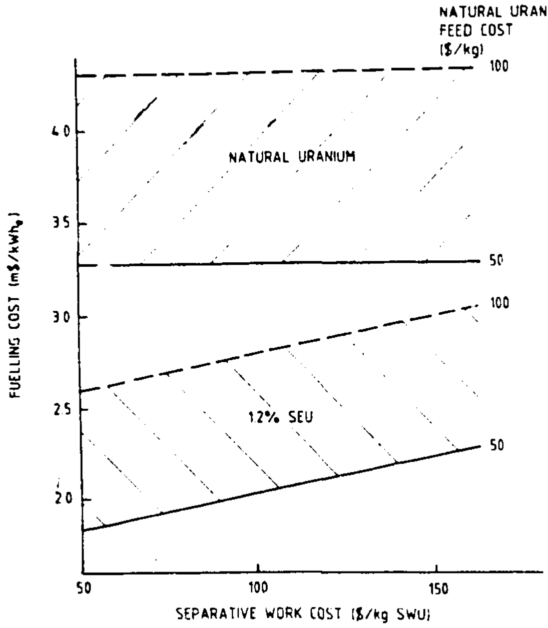


Fig. 3 Comparison of Equilibrium Fuelling Costs

It should also be noted that a recent study performed under the auspices of the Nuclear Energy Agency of the OECD concluded that a CANDU fuelled with natural uranium enjoys a fuelling cost advantage over PWR of a factor of two.[7]

Fuelling costs for an SEU-fuelled CANDU would be reduced significantly relative to natural uranium fuelling, depending on the burnup and the costs of natural uranium and enrichment services. With the current oversupply of enrichment capacity, the cost of enrichment has fallen and new enrichment technology promises to further decrease the cost. Figure 3 compares the equilibrium fuelling costs for CANDUs fuelled with natural uranium and 1.2% SEU, for a range of separative work unit (SWU) costs and natural uranium costs. Figure 4 shows that as the cost of enrichment decreases, the economically optimal enrichment increases. All costs quoted are in Canadian dollars. Table 1 contains the components of the fuelling cost for natural uranium and 1.2% SEU as well as the assumptions that are implicit in Figures 3 and 4.

Equilibrium SEU fuelling costs are significantly reduced, relative to natural uranium fuel, for a wide range of uranium and SWU costs, with enrichments in a relatively narrow range between 1.2% and 1.7%. Even though the additional uranium feed and the cost of enrichment makes an individual SEU fuel bundle more expensive than a natural uranium bundle, the additional energy extracted (due to the higher burnup) makes the cost per unit energy significantly lower, the difference depending on the relative natural uranium and SWU costs. Fabrication and back-end costs (per unit energy) are also reduced for SEU fuel, due to the smaller volumes of fuel involved. Since at this stage it is not certain what the difference will be between the back-end costs for natural uranium and SEU, the same value has been used in Table 1 for both fuels. Our initial assessment suggests that the difference in back-end costs (in $/kg) between natural uranium and slightly enriched uranium will not be large. Even if the disposal component of the back-end costs were a factor of two greater for SEU fuel than for natural uranium fuel, the SEU fuelling cost (per unit energy, in m$/kWhe) would increase by less than 4%. A more definitive assessment will be presented at the conference based on studies currently underway.

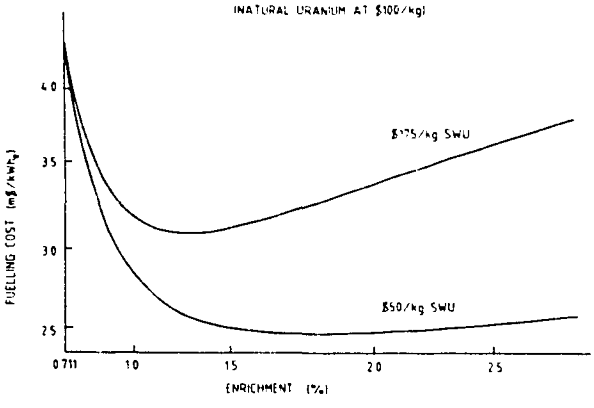


Fig. 4 Variation of Equilibrium Fuelling Cost with Enrichment

The so-called CANFURL fuel cycle (CANDU Fuelled with Uranium Recycled from LWR) is similar to the SEU cycle, but the enriched uranium is obtained from a different source.[8] The CANFURL cycle uses uranium separated from discharged LWR fuel without the need for further enrichment. Burnups of about 13 000 MWd/t should be achievable. On discharge from CANDU, the uranium content in the spent fuel is at about the same level as enrichment plant tails and there is no incentive for further recycle. Two factors affect the fuelling cost of the CANFURL cycle: the price at which reprocessed LWR uranium can be bought, and the fuel fabrication cost. The price of the reprocessed uranium is uncertain, and the fabrication cost may be more expensive than for natural uranium due to the presence of trace quantities of fission products. However the use of this material in CANDU is the most efficient and economical method of obtaining additional energy.

Uranium utilization in CANDU can be further increased by recycling plutonium extracted from

Table 1
Components of Equilibrium
Fuelling Cost

(m$/kWhe)

Component*		Natural Uranium	1.2% SEU
NU Feed		2.05	1.53
SWU @	$50/kg		0.20
	$110/kg		0.44
	$175/kg		0.70
Fabrication		1.23	0.54
Back-end		1.03	0.34
Total, SWU @	$50/kg	4.31	2.61
	$110/kg		2.85
	$175/kg		3.11

* Assumptions

Natural Uranium (U_3O_8)	$100/kg U
Natural Uranium (after conversion to UF_6)	$110/kg U
Conversion/Fabrication	
- Natural Uranium	$60/kg U
- SEU	$80/kg U
Back-end (temporary storage immobilization, permanent disposal)	$50/kg U
NU Burnup	7 000 MWd/t
SEU Burnup	21 300 MWd/t

spent natural uranium fuel, with either natural uranium (Pu/NU cycle) or depleted uranium (Pu/DU cycle). The depleted uranium can be obtained from enrichment plant tails. In these fuel cycles, mixed oxide (MOX) fuel for one generation is made up of the plutonium recovered from the spent fuel in the previous generation mixed with natural uranium or depleted uranium, along with any additional make-up plutonium from spent natural uranium fuel required to give the desired burnup. At a burnup of about 17 000 MWd/t, the Pu/NU cycle is self-sufficient in plutonium. Hence, this fuel cycle provides a means of generating energy from plutonium, while still preserving an inventory for future use in other reactor types, such as breeders. Within the burnup range 17 000 to 25 000 MWd/t, the improvement in uranium utilization for the Pu/NU and Pu/DU cycles is about 50%, compared to natural uranium in CANDU.

An attractive recycle option is the Tandem fuel cycle, in which the uranium and plutonium from spent LWR fuel is recycled in a CANDU reactor. This fuel cycle would require a simplified and cheaper reprocessing cycle, in which only the fission products are removed from the spent fuel. In a system consisting of a mixture of LWRs and Tandem-CANDUs, natural uranium savings of up to 40% could be achieved over the long term compared to an all-LWR system. Introduction of the Tandem-CANDUs could be an economic complement to LWRs.

Fuel cycles based on thorium are also feasible in CANDU and will be an attractive option when uranium prices increase significantly.[9] Since thorium has no fissile isotope a fissile fuel material is needed. The fissile and thorium fuels can be kept separate in the once through thorium cycle (OTT).[10] Two distinct fuel types, thorium and an enriched fuel are fed at different rates to the reactor and are not reprocessed. This cycle could compete economically with SEU and provides a method for the early introduction of thorium. However, the enrichment of the fissile fuel component is considerably higher than for SEU and practical fuel designs and fuelling strategies have still. to be confirmed.

Alternatively, a more conventional approach of mixing fissile material with thorium is possible.[6] These cycles are started with an initial inventory of fissile material and subsequently, some or all of the fissile component would be provided by recycled U-233. Introduction of these thorium cycles could reduce natural uranium requirements at equilibrium by 70% to 90% relative to the CANDU natural uranium cycle. A near breeding cycle is also possible, which at equilibrium would require no external fissile makeup. This near breeding cycle could become a breeding cycle by using highly purified heavy water and zirconium enriched in the low neutron-absorbing isotopes.

The current high cost of reprocessing does not make any recycle options economically attractive in either PWRs or CANDU at the present time, although local conditions may favour them in some countries.

TECHNICAL CONSIDERATIONS

Key technical areas that must be addressed when assessing the use of advanced fuel cycles are fuel management, reactor control, fuel performance and safety. Of these, fuel management is a central issue.

The design of current CANDU reactors is based on natural uranium fuel. Adjacent channels are refuelled in opposite directions (bi-directional refuelling), typically with 4 or 8 bundles added at a time. The locations of reactivity devices are based on the flux and power profiles associated with natural uranium fuel, which are highest near the centre of the fuel channels. The adjuster rods, which provide xenon override capability, are located near the axial midplane, thereby flattening the axial power profile (see Figure 5).

Enriched fuel (either SEU or MOX) is initially more reactive than natural uranium, and exhibits a larger change in reactivity during its stay in the reactor. In order that limits on maximum bundle and channel powers are not exceeded, fewer enriched bundles would be added during refuelling. If the same bundle shift scheme were used throughout the core with medium burnup fuel (about 21 000 MWd/t), the resultant axial power profile in the absence of adjuster rods would be highest at the refuelling end of the channel, and decrease along the length of the channel. The central location of the adjuster rods would depress the axial profile in the centre of the channel, increasing the peak bundle power for a given channel power, and reducing the effectiveness of the reactivity devices. This power profile is illustrated in Figure 5 for 1.2% enriched mixed uranium plutonium (MOX) fuel, using a 2-bundle shift throughout the core.

In existing CANDU reactors, power and reactivity control can be accomplished by the use of a suitable fuel management strategy. For example, the so-called checkerboard fuelling scheme, which makes use of the neutronic coupling between adjacent fuel channels, has been assessed.[11] In this strategy there is a central checkerboard of channel pairs, with both members of a pair fuelled with the same bundle shift, and with adjacent pairs fuelled with a different bundle shift. One possible strategy is to use 2- and 6-bundle shifts (Figure 6). On its own, a 2-bundle shift scheme in the central region of a core with adjuster rods would exhibit a double-humped power profile similar to that of Figure 7(a), while the 6-bundle shift on its own would exhibit a power peak near the centre of the fuel channel, as shown in Figure 7(b). When the checkerboard strategy is employed, the neutronic coupling between the channels blends the two profiles into a shape somewhat similar to that obtained with natural uranium fuel, as illustrated in Figure 7(c).

Time-dependent fuel management simulations have been performed for enrichments of 1.2% and 1.5%, for SEU and MOX fuels. These included an assessment of reactor control and safety aspects.

In future CANDU reactors, the locations of reactivity devices can be chosen to more easily facilitate the use of both natural uranium and enriched fuels.[12] For example, locating the adjuster rods in 4 rows, with the outer rods closer to the channel ends, would result in

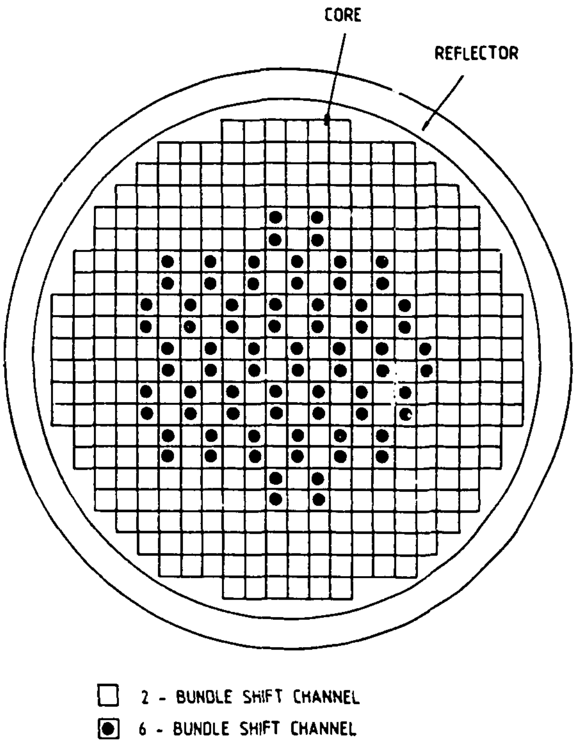


Fig. 5 Axial Power Profiles in CANDU (Normalized to 6500 kW Channel Power)

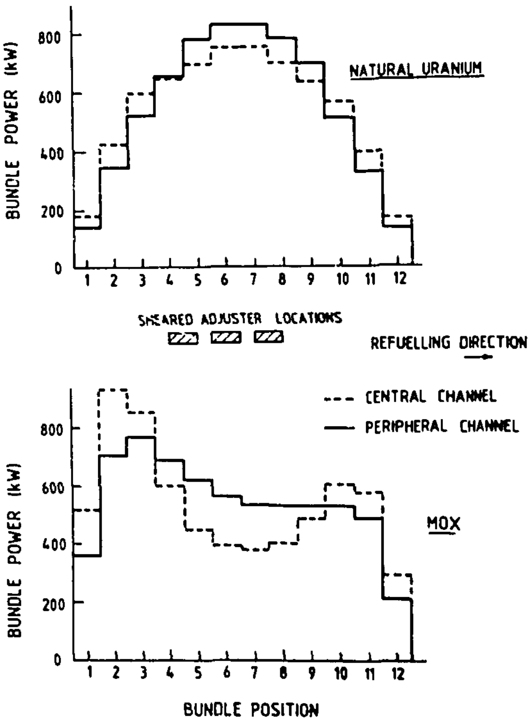
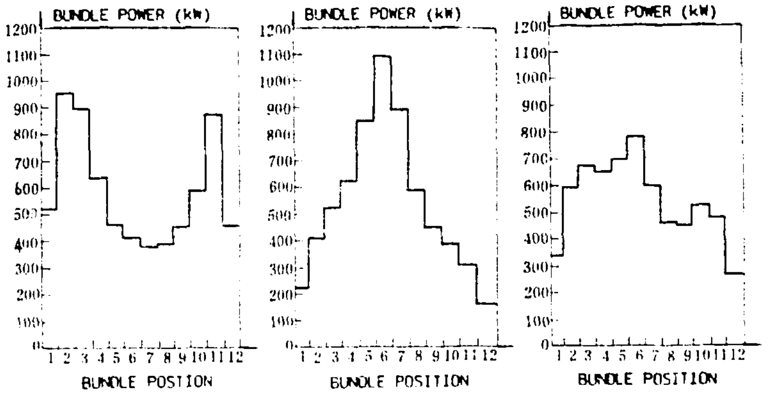


Fig. 6 Bundle Shift Pattern in the Checkerboarp Fuel Management Scheme



(a) 2-BUNDLE SHIFT SCHEME

(b) 6-BUNDLE SHIFT SCHEME

(c) 2-6 CHECKERBOARD SCHEME (6-BUNDLE SHIFT CHANNEL)

Fig. 7 Bundle Power Distribution Along a Channel
(Normalized to 6500 kW Channel Power)

significant improvement in the axial power profile for enriched fuels, and enable the use of a simple fuel management strategy throughout the core. The power profile with natural uranium fuel would not be significantly affected.

Fuel performance is another key technical consideration. The cumulative fuel bundle defect rate for natural uranium fuel in commercial CANDU reactors in Canada is less than 0.1% of the more than 500 000 bundles irradiated to date.

The current average discharge burnup of CANDU fuel is about 7 000 MWd/t compared with about 33 000 MWd/t in a PWR, but the fuel ratings and hence temperatures in CANDU fuel are significantly higher. Therefore, there is a need to show acceptable fission gas release from CANDU fuel if the burnup is increased by a factor of two or more. Additionally, the on-power fuelling of CANDU reactors subjects the fuel to changes in power level through the fuel lifetime.

The existing CANDU fuel performance data base includes both commercial power reactor experience and experimental results.[13,14] Over 3 000 natural uranium bundles have been irradiated to high burnup in experimental reactors, with burnups ranging up to 29 000 MWd/t. Some 66 enriched uranium fuel bundles have been irradiated to high burnup in experimental reactors. The results of these test irradiations are supplemented by the results from the irradiation of 173 single elements, either highly instrumented or containing specific features. The data show that the current CANDU fuel design is capable of reliable operation to burnups of at least 17 000 MWd/t under steady power conditions.

Thus there is confidence that fuel performance with current designs and under steady power conditions is satisfactory to 17 000 MWd/t. In order to introduce a fuel cycle with this burnup the verification of power ramp behaviour to approximately 17 000 MWd/t, plus a large scale demonstration in a commercial power reactor, would be required. To achieve burnups greater than 21 000 MWd/t a more subdivided bundle design could be used to reduce fuel rating, and thus improve fuel behaviour. A variety of technologies, such as graphite discs, hollow pellets, changes in clearances and fuel micro-structure, have also been tested or studied. These would be available to improve fuel performance, should they be required.

In order for fuel cycles with high fuel burnups to be adopted, fuel performance at high burnup must be demonstrated to be acceptable. This will require a statistically significant demonstration irradiation (e.g. 1 000 test bundles).

RESPONSE TO THE CURRENT ENVIRONMENT: CANADIAN NEAR TERM STRATEGY

Given the current high fuel-reprocessing costs and the low natural uranium and enrichment costs, the Canadian near term strategy is to concentrate primarily on the SEU fuel cycle.[15] This strategy will enable CANDU to maintain its competitive edge in fuelling costs and uranium utilization as the cost of enrichment falls.

All the advanced fuel cycles in CANDU are based on fuels with higher fissile content than natural uranium. The physics of fuel cycles such as MOX, CANFURL and TANDEM differ only in detail from the SEU cycle. Thus most of the results arising from the development of the SEU cycle will be applicable to these other fuel cycles.

Research and development activities within AECL cover all aspects of the SEU fuel cycle, including reactor physics, fuel development, and thermalhydraulics. While the emphasis is on the near-term, the program is aimed at both current and future reactors.

Reactor physics methods and models are being validated for enriched fuels. This involves experimental work in the zero energy facility ZED-2 and loop irradiations in research reactors at the Chalk River Nuclear Laboratories. Scenarios are being evaluated for the transition from natural uranium fuelling in CANDU to SEU fuelling. One key element in this program is the design of future CANDU reactors that could utilize either natural or enriched uranium fuels or be optimized for enriched fuels alone. The use of enrichment offers more flexibility in reactor design, allowing a trade-off between capital costs, fuelling costs, operating conditions, and component lifetimes. The optimal balance may not be the same for every customer, and enrichment offers the flexibility of choice.

The fuel development program is aimed at demonstrating that enriched fuels will reach their target burnups with the same very low fuel failure rate experienced with natural uranium fuel. This program includes irradiation of SEU fuel to high burnups, and the design of advanced fuel bundles.

Thermalhydraulic development includes both modelling, and full channel experiments to determine the effects of enrichment, bundle design and fuel management on the critical heat flux and critical channel power.

The work in advanced fuel cycles will ensure that safe, reliable and economical power from CANDU reactors is available well into the future.

CONCLUSION

The CANDU reactor has proven to be safe and economical, and has demonstrated outstanding performance with natural uranium fuel. Excellent neutron economy, coupled with on-power fuelling, permits the use of many different fuels and fuel cycles. CANDU fuel cycles can operate independently, using natural uranium, SEU, plutonium and thorium-based fuels, or in combination with LWRs. Fuel management strategies that would allow advanced fuel cycles to be used in existing CANDUs have been identified, while evolutionary design changes would allow even more flexibility, guaranteeing continuing superior performance for CANDU for many decades.

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