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## INTRODUCTION

Discharged fuel from light water reactors contains uranium with U-235 enrichment of between 0.7 and 0.95 wt%. This uranium, after separation and refabrication, can be used in CANDU or, after separation, re-enrichment and refabrication, in a light water reactor. The physics and economic implications of utilizing this uranium in these reactor systems is examined.

## CHARACTERISTICS OF RECOVERED URANIUM

Typical compositions for natural uranium, enriched uranium and reprocessed uranium, as given in Reference 1 are reproduced here in Table 1.

TABLE 1 TYPICAL URANIUM COMPOSITION			
	Natural	Enriched	Reprocessed
U-232	0.	0.	$1.1 \times 10^{-7}$
U-234	0.0055	0.03	0.02
U-235	0.72	3.25	0.91
U-236	0	0	0.42
U-238	99.275	96.72	98.65

The accumulation of the isotopes U-232, U-234 and U-236 introduces problems into the recycle of uranium.

U-232 is not present in fresh fuel. It poses a radiological hazard in both the re-enrichment and fuel fabrication stages. Because it is present in low concentration, it does not have reactor physics implications.

U-234 is present in natural uranium. Its concentration is increased by enrichment and, although it burns out, the concentration in reprocessed fuel is higher than natural uranium. It causes reactor physics problems due to neutron absorption and its alpha activity could pose problems in fuel fabrication.

U-236 is not present in fresh fuel. It builds up during irradiation and its neutron absorption presents major reactor physics problems.

## RECYCLE OPTIONS

There are four options by which reprocessed uranium can be used to reduce natural uranium requirements.

- blend with more highly enriched uranium and recycle in LWRs,
- re-enrich and recycle in LWRs,
- blend with natural uranium and enrich, and recycle in LWRs,
- use in CANDU.

Option (a) requires about 20% more SWU than is required either by Options (b) and (c) or by enriching natural uranium to the desired level. The combined effect of blending and discarding the fuel after three or so cycles is to reduce the uranium savings and SWU savings traditionally gained by uranium recycle by one third and one half, respectively (Reference 2). This option is not seen to be a long term solution.

Option (b) suffers from the problem of ever increasing levels of U-232, U-234 and U-236. The U-232 level in reprocessed uranium, Table 1, is already near the limit of acceptability at DoE enrichment plants (Reference 3). Multiple recycle may then be impossible due to contamination of the enrichment plant.

Option (c) resolves most of the problems already noted but still suffers from a slow build up of U-232, U-234 and U-236 and larger amounts of contaminated uranium.

In Option (d), the reprocessed uranium is fabricated into CANDU fuel bundles. At discharge, the U-235 concentration is at or below that of enrichment plant tails and can be discarded without the need for further recycle.

Because Option (a) i.e., blending with higher enriched uranium, does not appear to be a credible long-term option, only options (b), (c) and (d) will be considered further.

## METHODS OF ANALYSIS

The data to be presented were obtained from the United States code ORIGEN-2 (Reference 4). This widely used code has been validated for LWR and CANDU reactors. Several minor modifications were made to the code to enable easier set up of the necessary sequences of calculations. In addition, the capability of simulating an enrichment plant using the equations of de la Garza (Reference 5) was incorporated. Using these equations, the effect of enrichment on any uranium isotope can be calculated.

It is assumed that there is a cooling time of five years between the fuel being discharged and reprocessed, and that there is no loss of uranium in reprocessing, re-enrichment or fabrication. In all cases, when the uranium is re-enriched the tails assay is taken to be 0.25 % by weight. When light water reactor recycling is considered, the uranium is assumed to be recycled in the type of reactor, BWR or PWR, which produced it.

As discussed above, two recycling methods have been considered for LWR,

(1) No Blending. The discharged fuel is reprocessed, re-enriched, and refabricated. A sufficient number of reactors is assumed to be in the system to provide fuel for one recycle reactor.

(2) Blended. The discharged fuel from one reactor is reprocessed and blended with sufficient natural uranium before re-enrichment.

Recycle in CANDU of reprocessed uranium fuel discharged from LWRs after up to two prior recycles in an LWR has been considered.

**PHYSICS ASPECTS**

Effects Due to Initial Uranium Composition

All isotopes of uranium are present in the spent fuel. Three are of particular importance, U-232, U-234 and U-236. While U-232 is itself not radioactive, some of its daughter nuclides, e.g., Tl-208, are. Tl-208, with a half-life of about three minutes

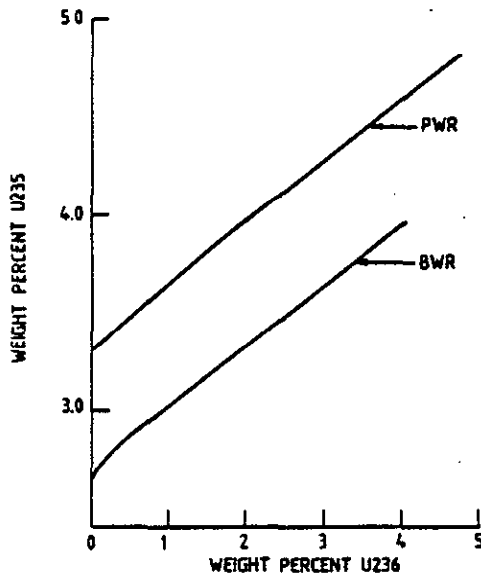


FIGURE 1 U235 ENRICHMENT TO COMPENSATE FOR U236

emits hard 2.6 Mev gamma radiation. U-232 is generated partly by alpha decay of Pu-236 with a half life of about 2.8 years. The U-232 content is then influenced by the cooling time before reprocessing. Problems can arise due to the radioactivity of the U-232 daughters during refabrication and re-enrichment.

U-234 and U-236 are neutron absorbers. Major effects are due to U-236 which, although having only a fairly small thermal neutron cross-section, has a significant resonance cross-section. The absorption in U-236 is then sensitive to the neutron spectrum. In the fairly hard spectrum of light water reactors, the resonance absorption is appreciable and to compensate for it the uranium must be enriched to a greater level than would be the case when natural uranium is used as the source material.

Figure 1 shows how the enrichment must be increased as a function of U-236 content for both PWR and BWR. In both cases, approximately an extra 0.3 % U-235 by weight is needed to compensate for each % by weight of U-236.

In the relatively soft neutron spectrum of CANDU, the U-236 has a less important role and only about an extra 0.044% U-235 by weight is needed to compensate for each % by weight of U-236.

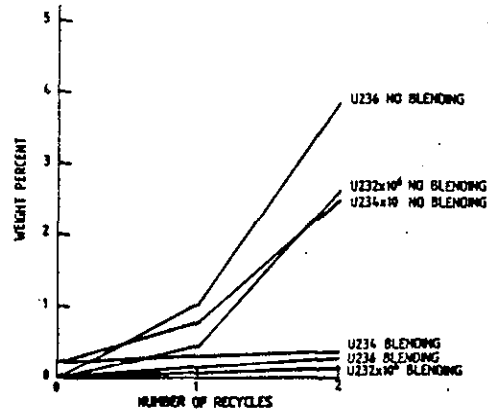


FIGURE 2a U232, U234, U236 WEIGHT PERCENT AT THE START OF AN IRRADIATION AS A FUNCTION OF NUMBER OF RECYCLES IN A BWR

When the fuel is recycled in light water reactors the adverse affects of these three isotopes increase as their concentrations increase. The concentration at the beginning of an irradiation is given in Figure 2a plotted against the number of recycles for a BWR and in Figure 2b for a PWR. The beneficial effect of dilution provided by the blending method of recycle is obvious.

Spent Fuel Properties

Multiple recycle in light water reactors requires increased initial U-235 enrichment. The residual U-235 enrichment in the discharged fuel also increases with the number of recycles as illustrated in Figure 3. In CANDU, the residual U-235 enrichment is always at or below the level of the tails assay of

an enrichment plant and there is no incentive to recover it.

With multiple blended recycle in light water reactors, the plutonium content, both total and fissile, of the spent fuel is essentially independent of the number of recycles while with no blending recycle it decreases. This is illustrated in Figures 4 and 5.

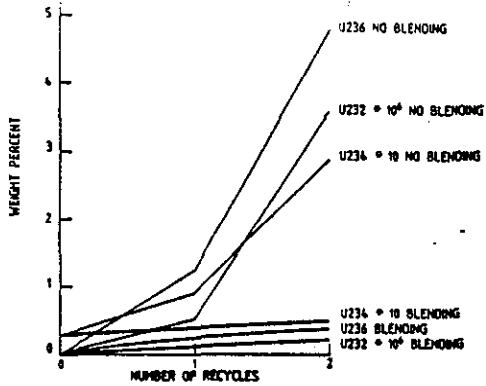


FIGURE 2b U232, U234, U236 WEIGHT PERCENT AT THE START OF AN IRRADIATION AS A FUNCTION OF NUMBER OF RECYCLES IN A PWR

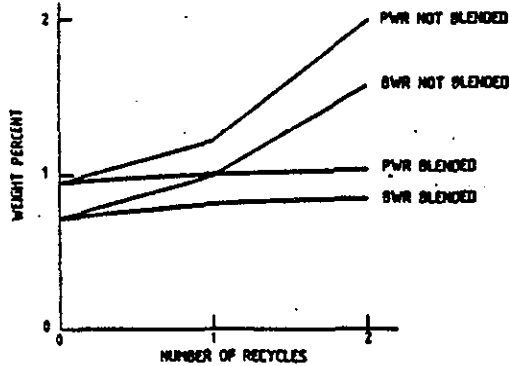


FIGURE 3 RESIDUAL WEIGHT PERCENT U235 AS A FUNCTION OF THE NUMBER OF RECYCLES

When recycled light water reactor uranium is used in CANDU, with the exception of fuel discharged after zero recycles from a BWR, the discharged fuel contains more plutonium than when CANDU is fuelled with natural uranium. However, the fissile to total plutonium ratio is less than with natural uranium fuel. This is directly attributable to the higher initial U-235 enrichment which enables the fuel to remain for a longer period in the reactor core. The zero recycle BWR fuel has an enrichment of about 0.71 wt%, but the U-236 reduces this to an effective enrichment which is less than that of natural uranium. The total plutonium and fissile plutonium produced in

CANDU is shown as a function of the number of prior recycles in a light water reactor in Figures 6 and 7.

The radioactivity and decay heat of the fuel after discharge from a light water reactor are not particularly sensitive to the number of recycles. These quantities depend primarily on the fuel burnup which is kept constant by changing the enrichment to compensate for the neutron absorption in U-234 and U-236.

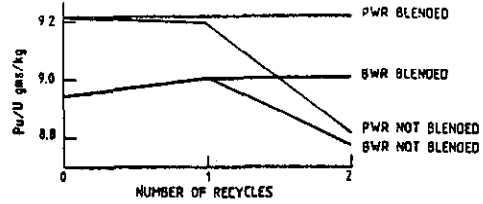


FIGURE 4 PLUTONIUM IN DISCHARGED LIGHT WATER REACTOR FUEL AGAINST NUMBER OF RECYCLES

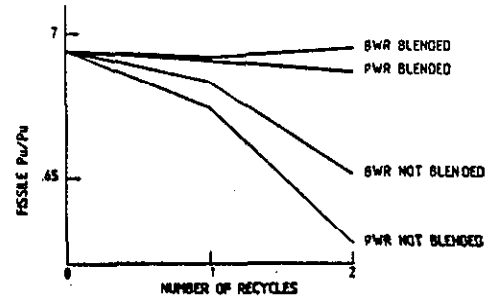


FIGURE 5 FISSILE PLUTONIUM IN DISCHARGED LIGHT WATER REACTOR FUEL AGAINST NUMBER OF RECYCLES

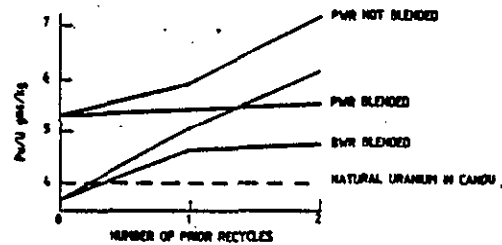


FIGURE 6 TOTAL PLUTONIUM PRODUCTION IN CANDU AGAINST NUMBER OF PRIOR RECYCLES IN A LIGHT WATER REACTOR

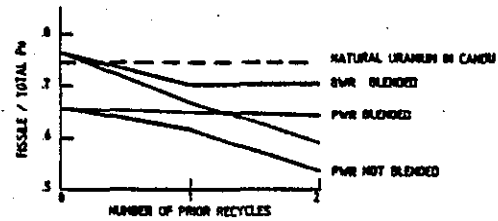


FIGURE 7 FISSILE TO TOTAL PLUTONIUM IN CANDU AGAINST NUMBER OF PRIOR RECYCLES IN A LIGHT WATER REACTOR

The radioactivity and decay heat of fuel discharged from CANDU are sensitive to the number of prior light water reactor recycles. Because the U-235 residual enrichment increases with the number of prior light water reactor recycles, the burnup in CANDU increases with the number of prior recycles. Correspondingly, the radioactivity and decay heat increase with the number of prior recycles. Figure 8a compares the radioactivity of recycled fuel from a BWR and from a CANDU fuelled with material recycled from a BWR. The corresponding results for PWR fuel are illustrated in Figure 8b.

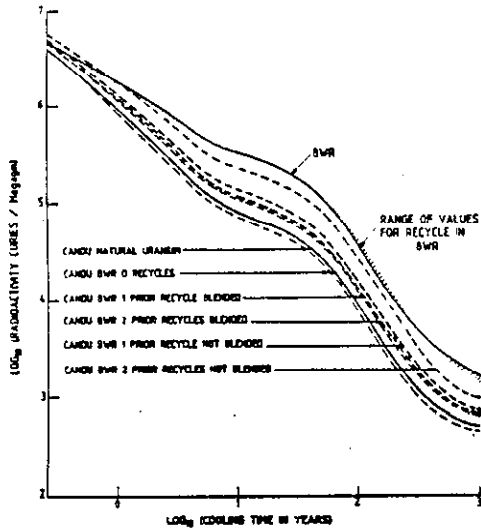


FIGURE 8a: RADIOACTIVITY AS A FUNCTION OF COOLING TIME BWR FUEL

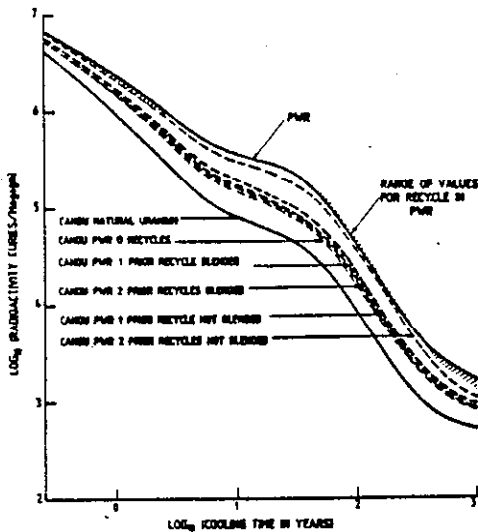


FIGURE 8b: RADIOACTIVITY AS A FUNCTION OF COOLING TIME PWR FUEL

### Energy Yield

Comparison of energy yield for the systems of reactors shown in Figure 9 will be made in terms of the burnup expressed as MWd/(kg of natural uranium). The burnup was assumed to be 31,500 MWd/t for a PWR, 27,500 MWd/t for a BWR, and 7,000 MWd/t for a natural uranium CANDU. The burnup achieved by CANDU when the various recycle fuels are used is given in Table 2.

Number of Prior LWR Recycles	CANDU Burnup (MWd/t)	
	PWR*	BWR*
0	13063	6211
1 Not Blended	17350	12181
2 Not Blended	27768	20235
1 Blended	13944	9496
2 Blended	14505	9977

\* - source reactor of reprocessed U

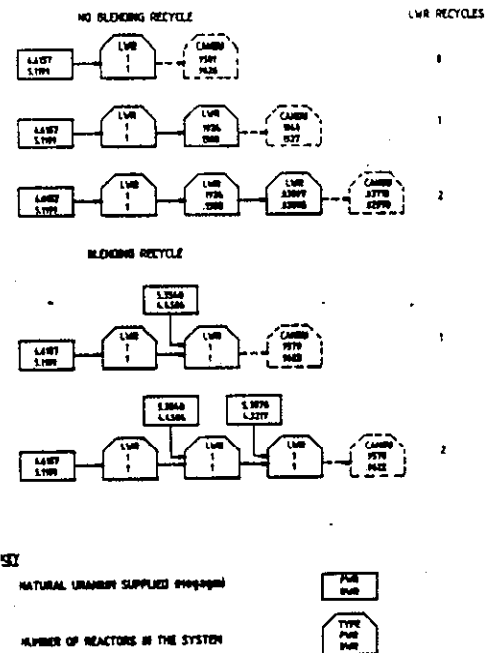


FIGURE 9: RECYCLE REACTOR SYSTEMS

For systems containing only light water reactors, the energy yield is shown plotted against the number of recycles in Figure 10. For systems containing light water reactors and CANDU, the energy yield is shown plotted against the number of prior light water reactor recycles in Figure 11.

In all cases the use of recycled uranium in CANDU increases the energy yield when compared to the case with an LWR replacing CANDU. In particular, after one recycle the increase in energy yield obtained with recycle in CANDU is between 2 and 4 times that obtained with recycle in a PWR, depending on the recycle method, and between 1.4 and 3 times that obtained with recycle in a BWR.

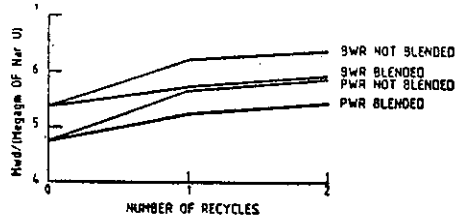


FIGURE 10 ENERGY YIELD FROM LWR SYSTEMS

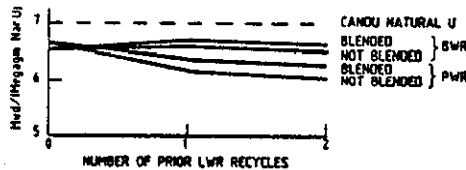


FIGURE 11 ENERGY YIELD FROM LWR PLUS CANDU SYSTEMS

#### ECONOMIC ASPECTS OF RECYCLE IN LWRs

Until quite recently, the value of the reprocessed uranium from spent LWR fuel has been of largely academic interest since only small amounts have been recovered and few utilities claimed a credit in establishing nuclear electricity generating costs. Now, however, increasing amounts are being recovered at the Cap La Hague reprocessing plant in France and more attention is being paid to the topic of uranium recycle (Reference 1, 13, 14). World-wide, the amount could increase to approximately 4000 Mg/annum by the end of the century if the planned additional reprocessing capacity is brought into operation in France, UK, Germany and Japan. Obviously there will be an incentive to gain the maximum economic advantage from these growing stockpiles.

In most analyses the recovered uranium has been valued according to its U-235 content, and a credit equivalent to the cost of producing such slightly enriched material in an enrichment plant has been assumed. Recycle of this material by re-enrichment would then give the same fuel cycle costs as enriched uranium produced from natural uranium feed. The discussion in the preceding sections, however, illustrates that this approach overvalues the recovered uranium and there are potentially four penalties to be applied in calculating the credit, if the costs for recycle are to be the same as for the initial cycle:

- the "neutron poison" effect
- a re-enrichment penalty
- a fabrication penalty
- a spent fuel penalty

#### Neutron Poison Penalty

The recovered uranium contains U-234 and U-236 and these are transmitted through the re-enrichment and refabrication processes. Consequently, fuel for insertion in the reactor must be enriched to a higher level to obtain the same burn-up as fuel made from natural uranium fuel. As a result, for a given mass of recovered uranium, less enriched fuel can be made and core separative work units used to produce the higher enrichment. Using the fuel cycle given in Table 1, as an example, the reprocessed uranium would have to be re-enriched to 3.52 wt% U-235 (because of the U-234 and U-236 content) to obtain the same burn-up as fuel made from a natural uranium feed which only requires an enrichment of 3.25 wt% U-235. If the reprocessed uranium were blended with natural uranium before re-enrichment then it could be enriched to a lower level, intermediate between 3.25 and 3.52 wt%. However, this is only because U-234 and U-236 would be distributed in a larger mass of enriched uranium and the penalty on the value would be similar.

Based on the above considerations, the value of the reprocessed uranium can be calculated from the value of the resultant enriched uranium. Although it is at a nominal 3.52 wt% U-235 enrichment, it only has a value equivalent to 3.25 wt% U-235 fuel when made from natural uranium. The results of the calculation are given in Table 3 below for a typical case.

Natural U Cost (as UF <sub>6</sub> )			
\$US 75/kgU			
Enrichment Cost			
\$US 150/kg SWU			
Reprocessed U Composition is given in Table 1.			
Enrichment Plant Tails (wt% U-235)	0.2	0.25	0.3
Reprocessed U Value - Based on U-235 Content Only (\$US/kg)	149.0	145.0	147.0
Reprocessed U Value - Based on U-234, U-235 and U-236 Content (\$US/kg)	120.0	119.0	123.0
Neutron Poison Penalty (\$US/kg)	29.0	26.0	24.0

The value of the reprocessed uranium depends on the cost of natural uranium, the cost of enrichment SWU and the tails enrichment at which the enrichment plant operates. For the assumed natural uranium and SWU costs, optimum tails would be approximately 0.3 wt% U-235 but it is known that some contracts are executed for non-optimum tails.

The effect of the U-234 and U-236 content is to lower the reprocessed uranium value by approximately 20% below the value based on U-235-content alone. Alternatively, for the assumed cost conditions, the neutron poison penalty can be assessed at approximately \$US 6/gram of contained U-234 and U-236 in the reprocessed uranium.

Re-Enrichment Penalty

Re-enrichment of reprocessed uranium poses difficulties in at least two areas. Depending on the mode of operation, there is the possibility that customers will receive enriched uranium contaminated with unwanted isotopes (U-232, U-234, U-236) regardless of the feed material they supply (Reference 6). The enrichment plant itself may become contaminated with the radioactive daughter products of U-232 decay leading to an increase in operating and maintenance costs. Obviously, in both cases, the importance of these effects increases as the supply of reprocessed uranium increases and forms a larger fraction of the uranium feed to the plant.

To guard against plant contamination, US DOE has placed an upper limit on U-232/U-235 ratio in the feed uranium at 0.11 ppm (Reference 3). The data in Table 1 illustrate that typical PWR reprocessed U may already exceed that limit and it should also be noted that this is a calculated value for the U-232 content and may be an underestimate (Reference 7). There are reports (Reference 8) that US DOE charges an enrichment premium on material that exceeds the specification and that other enrichment suppliers have more strict limits.

US DOE is currently reviewing its policy and charges for re-enriching reprocessed uranium, in the light of the expected increase in the volume of this form of feed (Reference 9). It seems possible, therefore, that re-enrichment in existing plants may be more costly than with fresh natural uranium feed but no supplier has yet published any data on the premium. One alternative could be the construction of dedicated enrichment facilities which handle only reprocessed uranium. Such an activity is again likely to need a higher enrichment price for commercial viability.

Fabrication Penalty

The fuel fabrication process may also be more expensive. The presence of U-232 daughter products and higher levels of U-234 may require modifications to the process to maintain personnel radiation exposure within limits. Parameters which will influence cost will include the concentration of these isotopes (particularly whether the uranium has been diluted with natural uranium before re-enrichment), and the time delay since re-enrichment.

Again however, no work has been reported which allows an estimate of the size of this potential penalty.

Spent Fuel Penalty

This penalty only has validity when recycling of reprocessed material has become established to the extent that credits for recovered material (uranium and plutonium) are included in establishing electricity rates. When reprocessed uranium is irradiated, the resultant spent fuel also contains uranium and plutonium which is recovered. However both materials contain even higher levels of undesirable isotopes. In the case of the uranium, the levels of U-232, U-234 and U-236 will have increased to an extent that the material cannot be recycled and is relatively valueless (Reference 10). The plutonium will contain levels of Pu-236 and Pu-238 which are

3-5 times higher and will so incur some fabrication cost penalty.

Consequently, the spent fuel credits will be considerably reduced relative to those for material which has not been recycled and this will further reduce the value of the reprocessed U.

In order to maintain the same fuelling costs, the reprocessed uranium must be valued significantly below its value based only on its U-235 content. Four penalties have been identified but the cost impact of only one can be estimated at this point in time. The maximum value of the uranium will be approximately 80% of its "U-235 equivalent" value and the other three penalties may result in further significant reductions.

ECONOMICS OF RECYCLE IN CANDU

It has been known for many years, that use of low-enriched uranium (LEU) in CANDU may produce lower fuelling costs than natural uranium fuelling, provided the cost of enrichment services is not too great (Ref. 11). Similarly, previous work (Ref. 12)

TABLE 4  
CANDU NATURAL U AND REPROCESSED LWR IN FUELLING  
ONCE-THROUGH EQUILIBRIUM COSTS  
(Canadian Dollars)

	Natural Uranium		Reprocessed LWR Uranium	
	\$/kgU	m\$/kWh	\$/kgU	m\$/kWh
Fuel Burnup (Mwd/kgU)	7.0		13.0 (1)	
Uranium	93.75 (2)	2.07 (4)	153.75 (3)	1.83 (4)
Fabrication	60.0	1.29 (5)	80.0	0.93 (5)
Spent Fuel Mgt	-	0.5 (6)	-	0.5 (6)
TOTAL		3.86		3.26

NOTES:

- (1) Based on Composition given in Table 1 and assumed burnup of 7.0 Mwd/kgU for natural uranium fuelling.
- (2) Equivalent to \$US 75/kgU (Table 3).
- (3) Equivalent to \$US 123/kgU (Table 3).
- (4) Calculated assuming 1.5 years lead time; 5% interest rate.
- (5) Calculated assuming 1.0 years lead time; 5% interest rate.
- (6) Assumed value for both cases, the impact of higher burnup is assumed compensated by the lower amount of fuel handled.

has established that fuelling with reprocessed PWR uranium may also result in significant savings.

Equilibrium fuelling costs have been calculated for two once-through cycles, one with natural uranium fuel and the other using reprocessed PWR U as fuel. The results are shown in Table 4 above.

It can be seen that using reprocessed uranium reduces the fuelling cost by approximately 0.6 m\$/kwh. This was calculated assuming this uranium was bought at its maximum value, i.e., no reduction for the re-enrichment, fabrication or spent fuel penalties discussed in the previous section. Obviously, owner utilities may be prepared to sell this material at lower prices to avoid the problems associated with recycle into LWR's. This advantage in fuelling cost will increase if the price of natural uranium increases or the cost of enrichment SWU falls. One assumption has been that the fabrication cost of the CANDU fuel using reprocessed uranium is only \$20/kgU higher than that for natural uranium fuel, i.e., a similar increase to that expected for "clean" enriched uranium (Reference 11). Preliminary investigations indicate that "open-shop" fabrication of this type of fuel should be possible and that no additional containment should be required. However, this aspect requires further work for verification.

In summary, use of reprocessed uranium in CANDU should lead to fuelling costs significantly lower than those for natural uranium fuelling, even when the uranium is purchased at its maximum value. It seems possible, in the future, that this uranium may be available at prices significantly lower than this maximum value and this could make this fuelling system even more attractive to a CANDU owner.

#### SUMMARY

Reprocessed LWR uranium contains two isotopes (U-232, U-236) not present in natural fuel. Buildup of these isotopes will limit the number of potential recycles in LWRs to only one; reduce the value of the uranium; and present difficulties to the establishment of large-scale recycling in LWRs. Use of this material in CANDU in a once-through cycle, however, will result in depletion of the U-235 content to below enrichment plant tails enrichment and the uranium can then be discarded with or without plutonium separation.

The energy yield in CANDU is approximately 80% greater; the economics are attractive; and fuel cycle costs could be significantly lower than natural uranium fuelling. These potential advantages to using this material in CANDU as opposed to recycle in LWRs and the possibility of a symbiotic LWR-CANDU system would appear to merit further consideration.

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