DISPOSAL COSTS FOR ADVANCED CANDU FUEL CYCLES

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ABSTRACT

The CANDU® reactor can "burn" a wide range of fuels without modification to the reactor system, including natural uranium, slightly enriched uranium, mixed oxide and spent LWR fuels. The economic feasibility of the advanced fuel cycles requires consideration of their disposal costs. Preliminary cost analyses for the disposal of spent CANDU-SEU (Slightly Enriched Uranium) and CANDU-DUPIC (Direct Use of spent PWR fuel In CANDU) fuels have been performed and compared to the internationally published costs for the direct disposal of spent CANDU and LWR fuels. The analyses show significant economic advantages in the disposal costs of CANDU-SEU and CANDU-DUPIC fuels.

INTRODUCTION

The CANDU® reactor is the only commercially available electrical generating system that can "burn" Natural Uranium fuel (CANDU-NU). Due to its neutron efficiency, on-power refuelling and "channel" design, CANDU has the flexibility to use a wide range of other fuels without modification to the reactor system (Boczar et al. 1997). Some advanced fuels being considered are:

- Slightly Enriched Uranium (CANDU-SEU), including recovered uranium from reprocessed spent LWR fuel (Suk et al. 1998);
- Mixed OXide (CANDU-MOX) with the plutonium obtained from either reprocessed spent LWR fuel or from the dismantling of weapons (Chan et al. 1997); and
- fuel derived directly from spent PWR fuel, so-called CANDU-DUPIC (Direct Use of spent PWR fuel In CANDU) (Sullivan et al. 1997).

The economic feasibility of any of these advanced fuels requires that all aspects of the fuel cycle be examined, including the back end (i.e., disposal). Recently, AECL has conducted preliminary cost analyses for the disposal of two types of advanced CANDU spent fuels - CANDU-SEU and CANDU-DUPIC - and has compared them to the costs for the disposal of spent CANDU-NU and PWR fuel. Specific spent fuels examined were:

- CANDU-NU (0.7 wt% ^{235}U) with nominal burnup (8000 MWd/Mg HE (heavy elements));
- CANDU-SEU at 0.9 wt% ^{235}U (14 000 MWd/Mg HE);
- CANDU-SEU at 1.2 wt% (21 000 MWd/Mg HE);
- CANDU-SEU at 1.5 wt% (28 000 MWd/Mg HE);
- CANDU-SEU at 1.7 wt% (32 000 MWd/Mg HE); and
- CANDU-DUPIC (56 000 MWd/Mg HE), the total burnup being the sum from the PWR stage (35 000 MWd/Mg HE) and the subsequent CANDU stage (21 000 MWd/Mg HE).

A natural uranium burnup of 8000 MWd/Mg HE is typical of several Canadian CANDU units. Actual burnup depends on details of the reactor, such as size and adjuster rod loading. The CANDU-SEU burnups are based on lattice cell calculations and are equivalent to a somewhat lower natural uranium burnup (i.e., they are conservative). The CANDU-DUPIC burnup (21 000 MWd/Mg HE) is also based on lattice cell calculations, with no adjustment of the spent PWR fuel composition (except for the removal and capture of gaseous and some volatile elements during processing).

BASIS FOR COMPARING COSTS

In deriving the spent-fuel disposal costs, the Canadian concept for deep geological disposal in plutonic rock was used as the reference base for design and costing, with in-floor borehole emplacement in a 1000-m deep repository and a 72-fuel-bundle-capacity, titanium-shell disposal container (Simmons and Baumgartner 1994). The interrelated key variations that were applied in the conceptual designs for the spent-advanced-CANDU-fuel repositories were:

- the post-irradiation age of the spent fuel before disposal (storage time);
- the number of spent-fuel bundles in a disposal container (Mg HE/container); and
- the number and spacing of containers across the width of a disposal room and their spacing along the length of the room.

Following the costing of the conceptual disposal designs, a common basis for comparing the costs of the options was needed. The OECD/NEA (1993) performed a study on the costs of high-level-waste disposal in geological repositories. Costs were normalized to the amount of electricity generated ($M/TWh US1991$). Currency differences and inflation rates were taken into account. Figure 1 shows a comparison where the estimated cost of spent-fuel disposal, prepared by several countries (open squares), including Canada, is plotted against the electricity generated from the corresponding fuel. The costs included waste packaging plant and disposal repository design, construction, operation, decommissioning and closure. Excluded from the costs were site screening, site selection and evaluation, waste storage and transportation, research and development and financing because these requirements varied considerably between countries. The exclusion of these costs allowed the comparison on a more common technical basis.

In general, a trend is displayed in Figure 1 for decreasing disposal costs per unit of electrical energy with increasing repository capacity (in terms of total electricity produced by the fuel). However, the significant differences in unit disposal costs, as shown by the wide bounds (dashed lines), reflect the large variation in the details of the technical design requirements for each of the countries (e.g., the waste emplacement method, nature of backfilling, type and post-irradiation age of spent fuel, temperature limits, disposal

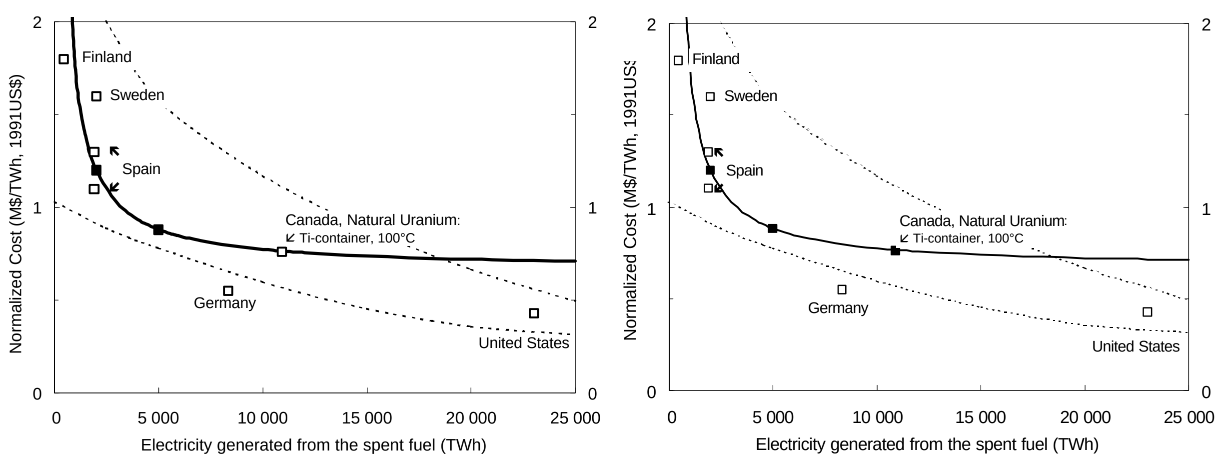

FIGURE 1 Unit cost for spent fuel disposal as a function of total electricity generated (after OECD/NEA 1993). CANDU-NU scaled costs included (solid line).

container design, etc.).

REFERENCE CASE AND VARIATIONS - CANDU-NU FUEL

Figure 1 also shows the variation of the unit disposal cost for spent CANDU-NU fuel (solid squares and line) calculated for three repository capacities (i.e., for three different values of total electricity produced from corresponding quantities of spent fuel). The unit disposal costs ($M/TWh US1991$) for each capacity are composed of three components:

- unit operating costs (constant with the quantity of electricity or corresponding waste produced);
- unit construction and decommissioning variable costs (constant with the quantity of electricity or corresponding waste produced); and
- unit construction and decommissioning fixed costs (inversely proportional to the quantity of electricity or corresponding waste produced).

TABLE 1 Unit disposal costs for all cases

Case Study	Container		Fuel Age (a)	Unit Disposal Cost ($M/TWh US1991$)		
	Material	Temp. (°C)		2000 TWh	4321 TWh	10 000 TWh
CANDU-NU						
	Ti	100	10	1.20	0.95	0.77
	Ti	90	10	1.36	1.01	0.84
	Cu	90	10	1.45	1.10	0.93
CANDU-SEU						
0.9 wt%	Ti	100	10	1.19	0.84	0.67
	Ti	100	50	1.11	0.76	0.59
1.2 wt%	Ti	100	10	1.16	0.81	0.64
	Ti	100	50	1.03	0.68	0.51
1.5 wt%	Ti	100	10	1.19	0.84	0.67
	Ti	100	50	0.99	0.64	0.47
1.7 wt%	Ti	100	10	1.36	1.01	0.84
	Ti	100	50	0.97	0.63	0.46
CANDU-DUPIC						
	Ti	90	50	1.06	0.64	0.43
	Cu	90	50	1.08	0.65	0.44

The cost curve shown in Figure 1 is useful for comparing cases and is included in all the following figures as the reference case (also see Table 1). Note that the solid line extends beyond the estimated bounds of the unit disposal costs projected by the OECD/NEA. The bounds are estimates only and are not fully representative of the asymptotic behaviour of the unit disposal cost curves.

In Figure 2, two additional curves (i.e., Ti-container, 90°C and Cu-container, 90°C) show the effect on unit disposal costs by reducing the temperature design limit on the outer surface of the disposal container from 100°C to 90°C (also Table 1). This reduction of temperature results in an increase in repository size (i.e.,

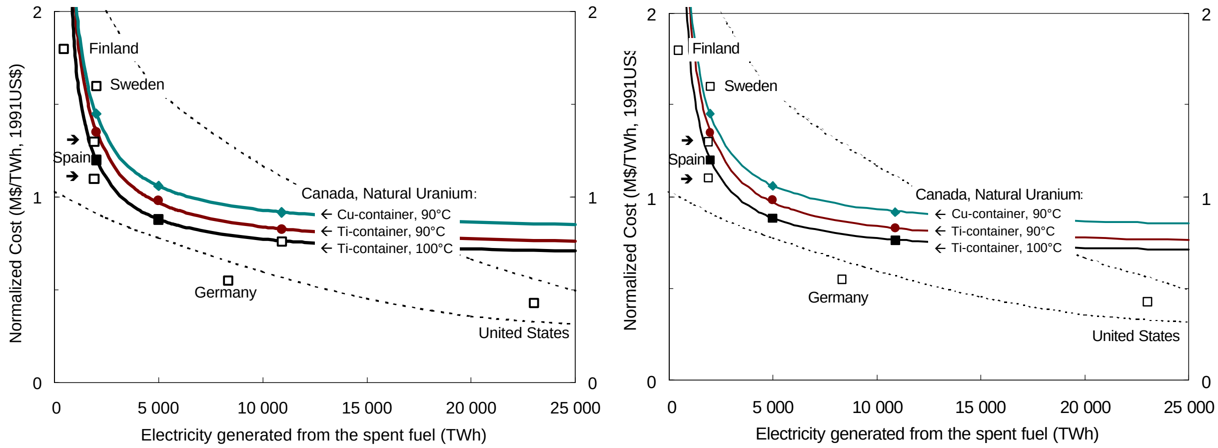

FIGURE 2 Canadian CANDU unit cost for spent fuel disposal: Effect of change in temperature design limits and change in container material.

increase in spacing between containers within a disposal room, increase in length or quantity of rooms, increase in total length of tunnels, thus, an increase in the waste emplacement area of the repository). Also, if the titanium (Ti) container is replaced with a more expensive copper (Cu) container, the unit disposal cost also increases, as expected, although the effect is generally less than 10%. The reference case is shown as the lowest curve.

CANDU-SEU DISPOSAL COSTS

The unit disposal costs for 1.2 wt% SEU are lower than for natural uranium fuel (Figure 3, Table 1). Less spent fuel needs to be packaged into fewer costly disposal containers although the repository size is increased. However, for the 1.7 wt% CANDU-SEU case, the unit disposal cost is greater than the reference CANDU-NU case because the cost saving from fewer containers is exceeded by the increased container spacing and size requirements for the repository. All these cases are based on 10 years of post-irradiation storage.

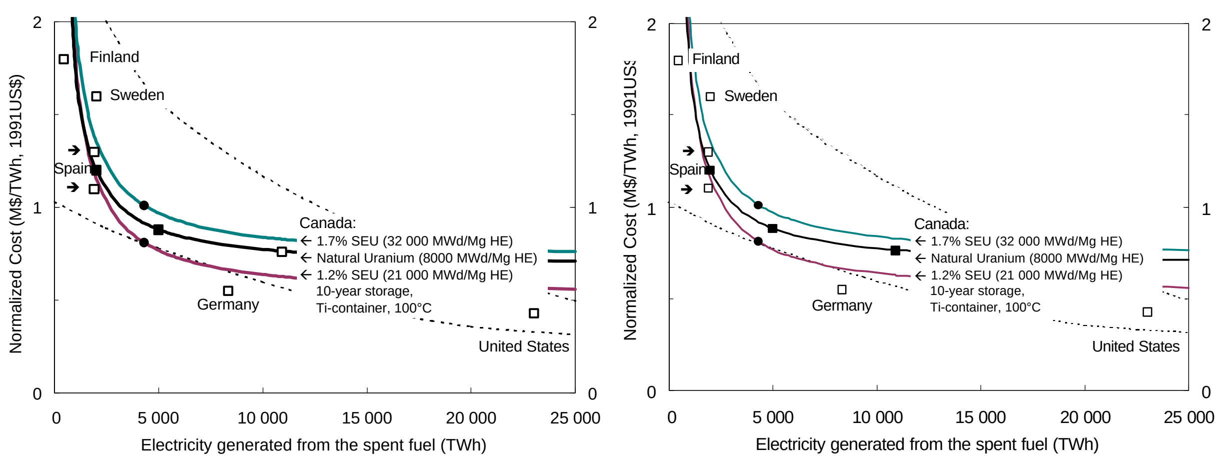

FIGURE 3 Canadian CANDU unit cost for spent fuel disposal: Effect of change in fuel enrichment and burnup (SEU 10-year post-irradiation storage).

If the storage period for spent CANDU-SEU fuel is increased from 10 to 50 years to allow for more thermal decay, the unit disposal costs for disposal are significantly reduced (Figure 4). This is also clearly shown in Figure 5 for the full range of potential spent CANDU-SEU fuels for an electrical-generation case of 4321 TWh (generated by 4 million CANDU-NU fuel bundles).

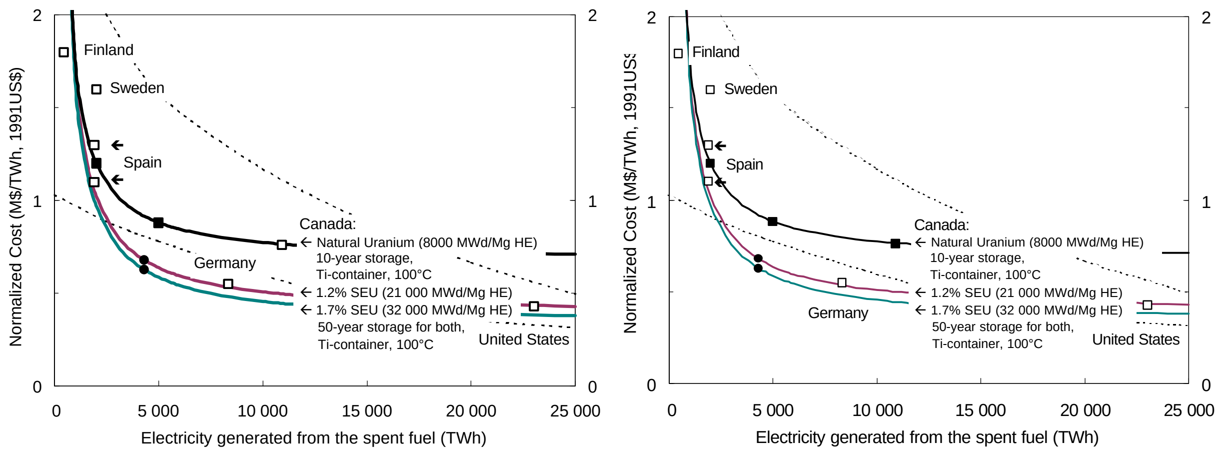

FIGURE 4 Canadian CANDU unit cost for spent fuel disposal: Effect of change in fuel enrichment and burnup (SEU - 50-year post-irradiation storage).

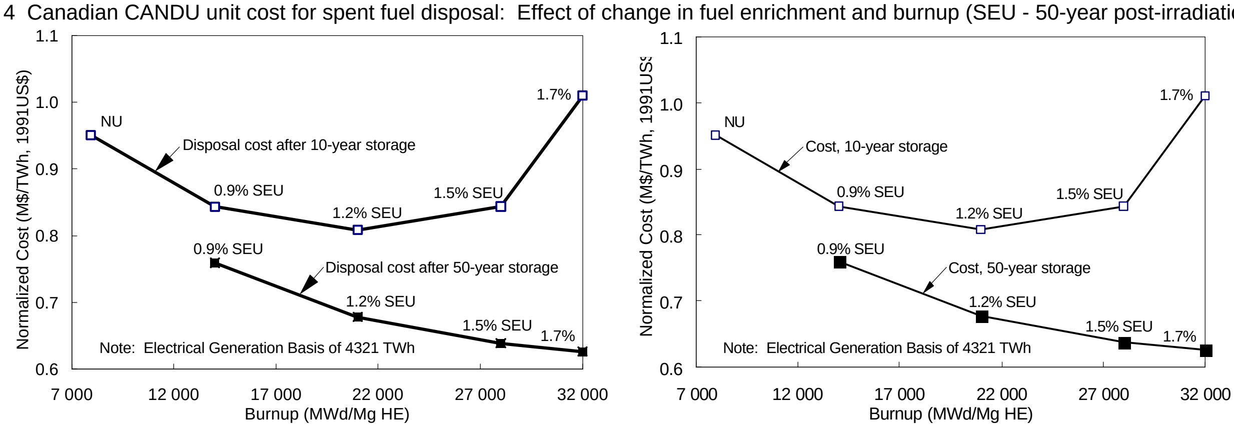

FIGURE 5 Canadian CANDU unit cost for spent fuel disposal: Comparison of spent CANDU NU and SEU fuels as a function of burnup (enrichment) and post-irradiation storage (based on a total electrical generation of 4 321 TWh and OECD/NEA (1993) basis).

Disposal cost savings of up to 15%, relative to CANDU-NU, can be achieved for 1.2 wt% CANDU-SEU fuel after 10 years of post-irradiation storage. The cost savings can be further improved to a maximum of about 30%, if post-irradiation storage is extended to 50 years. The number of disposal containers and, thus packaging costs, do not change for the increase in storage period. Only the repository costs decrease (i.e., decrease in repository size) with the increase in storage time. As noted, post-irradiation storage costs are not included in any of the analyses.

An enrichment of about 0.9 wt% is of current interest for CANDU in offering significant fuel-cycle and other operational benefits. This enrichment can be provided either as SEU or as recovered uranium from the reprocessing of spent LWR fuel. Disposal cost savings of about 10% (10-year stored) to 20% (50-year stored) compared to natural uranium (10-year stored) are indicated for spent 0.9 wt% CANDU-SEU fuel (Table 1).

CANDU-DUPIC FUEL

DUPIC Fuel Characteristics

The reference CANDU-DUPIC fuel cycle assessed in this study begins with "typical" PWR fuel burned to an average discharge burnup of 35 000 MWd/Mg HE. The fuel is stored for 10 years after discharge from the reactor. The spent PWR fuel pellets then undergo a series of oxidation/reduction cycles ("OREOX" process), are reconstituted into new CANDU fuel pellets, loaded into fuel sheaths which are then assembled into CANDU fuel bundles. The bulk of the volatile, semi-volatile and gaseous fission products are assumed to be driven off and captured in the OREOX process. In the reactor physics and decay-heat computer modelling, the removed products are assumed to be:

- 100% of ^{3}H, Xe and ^{14}C;
- 99% of Te, I, Cs and Kr; and
- various percentages of Se, Mo, Tc, Ru, Rh, Pd and Ag (semi-volatiles).

This DUPIC fuel is then burned in the CANDU reactor for an additional 21 000 MWd/Mg HE. As noted earlier, the actual burnup in the CANDU stage will depend on the details of the fuel design. The total effective burnup of the spent CANDU-DUPIC fuel is equivalent to about 56 000 MWd/Mg HE.

Figure 6 compares the decay heat from three spent-fuel types: PWR, CANDU-NU and CANDU-DUPIC. These data are generated by a series of coupled multiregion WIMS-AECL/ORIGEN-S simulations. A surprising observation is that the decay heats for the spent CANDU-DUPIC and PWR fuels are similar. Although an additional 60% of energy is derived from the spent PWR fuel by recycling it as CANDU-DUPIC, the decay-heat load is largely unchanged.

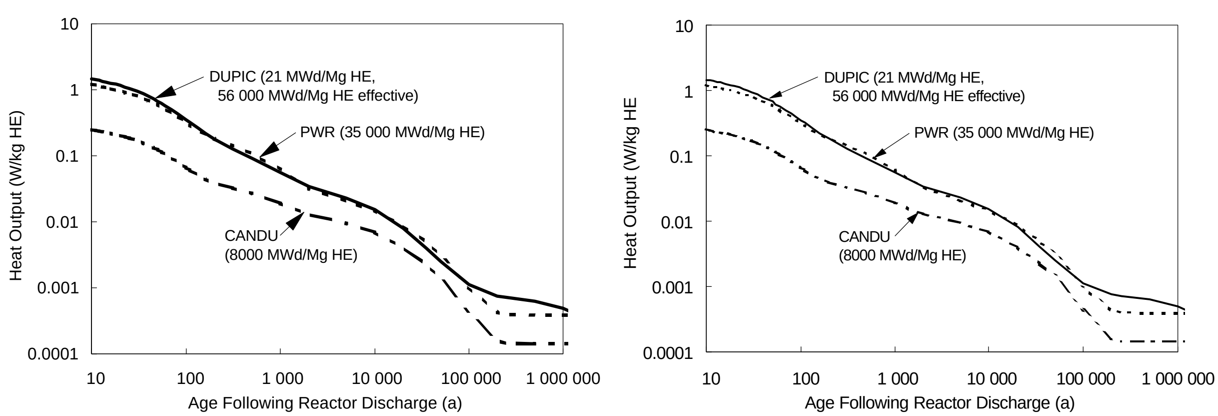

FIGURE 6 Heat decay characteristics of spent fuels

In spent CANDU and PWR fuels, the fission-product-decay heat generally dominates the total decay heat for a period of <100 years. Soon after discharge from the PWR, the main decay heat contributors are ^{134}Cs, ^{137}Cs and ^{137m}Ba. The ^{137m}Ba is considered part of the ^{137}Cs decay-heat source term because of its very short-lived metastable decay state.

Following 10 years of post-irradiation storage, Cs (and ^{137m}Ba) is extracted from the spent PWR fuel by the OREOX process. This represents about 50% of the fission-product-decay heat or about 40% of the total-decay heat (see Table 2). With the removal of Cs, the period of fission-product-decay-heat dominance in the subsequent spent CANDU-DUPIC fuel is decreased to less than 10 years (solid line in Figure 6).

TABLE 2 Decay heat from spent PWR fuel

	Decay Heat (W/kg HE)				
	Discharge	*0.1 year*	*1 year*	*10 year*	*100 year*
Total	2.460×10^{3}	5.071×10^{1}	1.102×10^{1}	1.211×10^{0}	3.105×10^{-1}
Actinides	1.319×10^{2}	1.448×10^{0}	5.106×10^{-1}	2.340×10^{-1}	2.087×10^{-1}
Fission Products	2.328×10^{3}	4.926×10^{1}	1.051×10^{1}	9.768×10^{-1}	1.018×10^{-1}
Elemental Cs	1.574×10^{2}	1.819×10^{0}	1.307×10^{0}	1.585×10^{-1}	1.264×10^{-2}
Elemental Ba	9.155×10^{1}	1.207×10^{0}	4.156×10^{-1}	3.376×10^{-1}	4.219×10^{-2}

An important actinide-decay-heat source is ^{241}Am (i.e., from ~50 to ~1000 years after discharge). Much of the initial ^{241}Am inventory that is present in the fabricated CANDU-DUPIC fuel is removed during irradiation in the CANDU reactor. The ^{241}Am that built in from ^{241}Pu decay in the spent PWR fuel is readily converted in the CANDU reactor to ^{242}Am and ^{242m}Am via neutron capture. The ^{242m}Am undergoes neutron capture to ^{243}Am or undergoes fission. Most ^{242}Am undergoes fission or beta-decay and electron-capture. The neutron cross sections and decay rates for these reactions are quite large, so the concentration levels of ^{242}Am and ^{242m}Am remaining in the CANDU-DUPIC fuel are quite small on a continuing basis.

The levels of ^{241}Pu and ^{241}Am adjust to balance generation and depletion reactions during the CANDU stage irradiation. The concentration of ^{241}Pu at discharge is greater in PWR fuel than in CANDU-DUPIC fuel. Conversely, the concentration of ^{241}Am at discharge is greater in CANDU-DUPIC fuel than in PWR fuel. Eventually, the decay heat from ^{241}Am becomes greater in the decaying spent PWR fuel than in the decaying spent CANDU-DUPIC fuel, due to ^{241}Am build in from ^{241}Pu decay.

The total decay heat from ^{239}Pu and ^{240}Pu in both spent fuels are similar over the first 1000 years after discharge. The ^{240}Pu component is greater in the spent CANDU-DUPIC fuel, reflecting the larger cumulative fuel irradiation than in the spent PWR fuel. Since ^{239}Pu decays more slowly than ^{240}Pu, eventually the decay-heat component from ^{239}Pu becomes the dominant actinide-decay-heat source for several hundred thousand years.

In summary, the decay-heat characteristics of the higher burnup spent CANDU-DUPIC fuel are similar to that of spent PWR fuel due to:

- the extraction of Cs in the spent PWR fuel in the OREOX process ;
- the transmutation of ^{241}Am from the spent PWR fuel in the CANDU reactor;
- the consumption of ^{241}Pu from the spent PWR fuel in the CANDU reactor; and
- the consumption of ^{239}Pu relative to ^{240}Pu in the CANDU reactor.

Spent CANDU-DUPIC Fuel Disposal Costs

In the conceptual design analysis for disposal of spent CANDU-DUPIC fuel, we found, because of its high heat output, that the amount of fuel in a disposal container must be:

- reduced from 72 fuel bundles (1314 kg HE) to 60 bundles (1095 kg HE); and
- stored for 50 years following discharge from the CANDU reactor before disposal, to achieve the 90°C temperature design limit.

Cost results are shown in Figure 7. Unit total costs for spent CANDU-DUPIC fuel disposal are less than for spent CANDU-NU and CANDU-SEU fuels. Generally, the unit total costs for spent CANDU-DUPIC fuel disposal are estimated to be considerably less than for spent PWR fuel in other countries

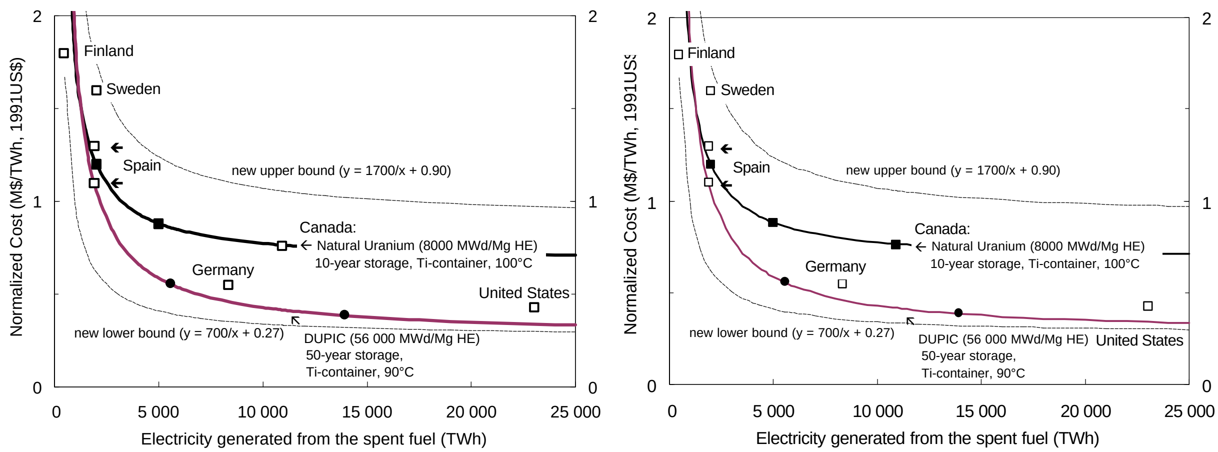

FIGURE 7 Canadian CANDU unit cost for spent fuel disposal: Effect of recycling spent PWR fuel in CANDU reactor (DUPIC fuel cycle).

OREOX Process By-Products

The costs for the immobilization, encapsulation, storage and disposal of the by-products listed previously for the DUPIC fuel preparation remain to be investigated. The removal of Cs from the spent PWR fuel during fuel processing contributes to the reduced heat generation by the spent CANDU-DUPIC fuel. To evaluate the feasibility of surface storage of Cs that is released from spent CANDU-DUPIC fuel during processing, we have considered the possibility of storing it in a concentrated, immobilized form in concrete canisters similar to those that are currently deployed for spent CANDU-NU fuel storage at the Point Lepreau nuclear generating station in New Brunswick, Canada. The maximum design heat loading in these canisters, each of which is used to store 540 CANDU-NU fuel bundles, is 3200 W. This is equivalent to ~19 kg of Cs in ~7.3 Mg HE of 10-year-stored spent PWR fuel.

Lab-scale tests with low-density (~500 kg/m^3) ceramic filters show that Cs can be efficiently trapped at loadings of 30-40% of the original filter mass. Thus, 19 kg of Cs could be trapped on about 60 kg (0.12 m^3) of unconsolidated filter. Even if Cs filters are removed from the DUPIC fuel processing system before they reach saturation, and if they remain uncompacted, their volume can be easily accommodated in a typical fuel-storage canister. Filters may undergo volume reduction and encapsulation before storage.

The maximum initial thermal load for a disposed waste container of the size used in these studies is about 1000 W (Baumgartner et al. 1994). Thus, the combination of the Cs waste loading in the disposal container (thermal density) and length of storage prior to disposal (discharge age of waste) need to be considered.

The costs for the disposal of the *other* by-products also remains to be examined. Radio-nuclides, such as ^{3}H, ^{14}C, ^{85}Kr and ^{129}I, and possibly also semi-volatile species such as ^{99}Tc, may need to be separated from the off-gases and immobilized. The recovery and immobilization of these radionuclides has received considerable attention in the conventional fuel-reprocessing industry, as reviewed by Taylor (1990a, 1990b, 1991). Although, in many cases, this work has not proceeded beyond bench or pilot-scale studies, it appears that feasible methods are available to immobilize these radionuclides. From a thermal perspective, disposal of these other by-products is considered simpler because they are very minor heat-generating radionuclides.

OECD/NEA UNIT DISPOSAL COST BOUNDS

In the course of comparing our unit disposal costs to the information provided by the OECD/NEA (1993), we observed that their projected upper and lower unit disposal cost bounds (Figure 1, etc.) did not fully encompass our estimates. We suggest a new range of unit-cost bounds (Figure 7, dashed lines), that bound all the unit disposal cost data and reflect the hyperbolic nature of the unit disposal cost basis.

CONCLUSION

These preliminary cost analyses show that the direct disposal of advanced spent CANDU fuels (i.e., CANDU-SEU and CANDU-DUPIC) are economically feasible. In most cases, significant unit energy cost savings may be achieved as compared to spent CANDU-NU fuel. Other cost factors, omitted in the disposal cost analyses, including the storage costs, the immobilization, encapsulation and disposal of the by-products from the CANDU-DUPIC fuel preparation, research and development, siting, transportation and financing, must still be considered.

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KEY WORDS

CANDU, DUPIC, disposal, costs, repository, advanced fuel, SEU.