THE BACK END OF THE FUEL CYCLE AND CANDU

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Abstract

CANDU reactor operators have benefited from several advantages of the CANDU system and from AECL's experience, with regard to spent fuel handling, storage and disposal. AECL has over 20 ye0ars experience in development and application of medium-term storage and research and development on the disposal of used fuel. As a result of AECL's experience, short-term and medium-term storage and the associated handling of spent CANDU fuel are well proven, and economic with an extremely high degree of public and environmental protection. In fact, both short-term (water-pool) and medium-term (dry canister) storage of CANDU fuel are comparable or lower in cost per unit of energy, than for PWRs. Both pool storage and dry spent fuel storage are fully proven, with many years of successful, safe operating experience. AECL's extensive R&D on the permanent disposal of spent-fuel has resulted in a defined concept for Canadian fuel disposal in crystalline rock. This concept was recently confirmed as "technically acceptable" by an independent environmental review panel. Thus, the Canadian program represents an international demonstration of the feasibility and safety of geological disposal of nuclear fuel waste. Much of the technology behind the Canadian concept can be adapted to permanent land-based disposal strategies chosen by other countries. In addition, the Canadian development has established a baseline for CANDU fuel permanent disposal costs. Canadian and international work has shown that the cost of permanent CANDU fuel disposal is similar to the cost of LWR fuel disposal, per unit of electricity produced.

1. POOL STORAGE OF SPENT CANDU FUEL

When a CANDU natural uranium fuel bundle is discharged from the reactor, after 12-18 months of irradiation, it is removed to a pool system for interim storage Ref. [1]. The water in the pool removes the residual heat produced by the spent fuel and provides radiation shielding for workers. The compact design of the CANDU fuel bundle, and the impossibility of criticality for CANDU natural uranium spent fuel bundles in water pool storage, make for extremely simple and hence economical pool storage. Packing density is determined by heat transfer considerations and not by criticality concerns.

To prevent leakage, and hence potential releases to the environment, the spent fuel pool has double concrete walls, designed such that any leakage through the inner wall would enter drains between the walls and flow to a cleanup system. The water shields the radiation emitted by the spent fuel, and the heat generated by the radioactive decay is transferred to the water. The water is cooled by circulating it through heat exchangers and is purified by filters and ion exchange systems that remove any dissolved and suspended radionuclides. The spent fuel bays are designed to meet applicable seismic requirements.

For its latest designs, the spent fuel bay proposed by AECL is designed to store irradiated fuel bundles in stainless steel baskets. The hexagonal baskets store 60 fuel bundles with the bundle axes vertical. The baskets can be stacked six-high. This storage arrangement provides the ability to store fuel from up to 20 years of operation. It also simplifies fuel handling operations, because the hexagonal baskets are designed for direct transfer to dry spent fuel storage, with no change of carrier required. Fuel handling operations are straightforward because, as mentioned above, criticality accidents are not a concern.

2. DRY STORAGE OF SPENT CANDU FUEL

After spent CANDU fuel has been out of the reactor for about six years, its activity and rate of heat generation have decreased sufficiently to allow the fuel to be transferred to dry storage if desired. Compared with wet storage, dry storage is considered to have the advantages of:

- Reduced amounts of radioactive waste, such as filters;
- Less potential for contamination of the storage facility;
- Little or no corrosion of fuel sheaths;
- Less radiation exposure to operating personnel;
- Minimal maintenance; and
- Low operating costs.

Dry storage is simple to implement and modules can be added as needed. Furthermore, there is low exposure of operating personnel, triple containment of the spent fuel radioactivity and little or no radioactive waste such as the used filters from pool storage water cleanup systems.

AECL started to study dry storage for spent nuclear fuel in the early 1970s. Silo-like structures called concrete canisters were first developed for the storage of research reactor enriched uranium fuel and then perfected for spent CANDU natural uranium fuel. By 1987, concrete canisters were being used for safe and economical storage of all spent fuel accumulated during the operation of AECL's decommissioned prototype reactors (Table I). Each canister contains a stack of spent fuel baskets, illustrated in Fig. 1.

The same basic technology was then applied to on-site dry storage of spent fuel generated by operating CANDU nuclear power generating plants. New Brunswick Power and Korea Electric Power Company selected AECL's concrete canister technology for their CANDU-6 nuclear generating stations at Point Lepreau (1989) and Wolsung-1 (1990) (Table I).

In 1989, AECL began development (in cooperation with Transnuclear, Inc.) of a monolithic, air-cooled, concrete structure for dry storage called MACSTOR (see Figs 2&3). MACSTOR modules require less land area than concrete canisters for the same amount of spent fuel and are suitable for storage of spent fuel assemblies from other reactor types (PWR, BWR, VVER) as well as CANDU. In 1995, Hydro-Québec built the first such system for dry storage at the Gentilly-2 CANDU-6 nuclear generating station (Fig. 2) [2].

Dry storage costs for spent fuel from a CANDU reactor design have been compared to those for a typical pressurized light water reactor both normalized to a gross power of 1000 MW(e) [3]. The results indicated that the dry storage costs for the CANDU system were about 30% lower than the LWR system.

TABLE I CANDU SPENT FUEL CURRENTLY IN DRY STORAGE

Reactor Unit	Fuel	Number of Canisters
Whiteshell Research	17 MgU	11
Gentilly-1	67 MgU	11
Douglas Point	298 MgU	47
Nuclear Power Demonstration	75 MgU	11
Pt. Lepreau	2790 MgU (lifetime)	275 (lifetime)
Wolsong-1	2790 MgU (lifetime)	275 (lifetime)
Gentilly-2	2790 MgU (lifetime)	275 (lifetime)

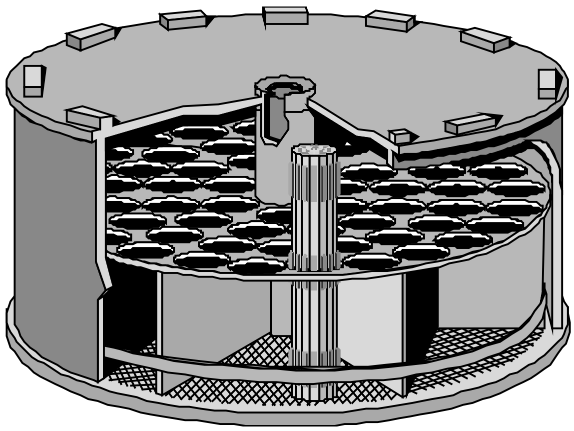

FIG. 1. Basket Holding 60 CANDU Spent Fuel Bundles

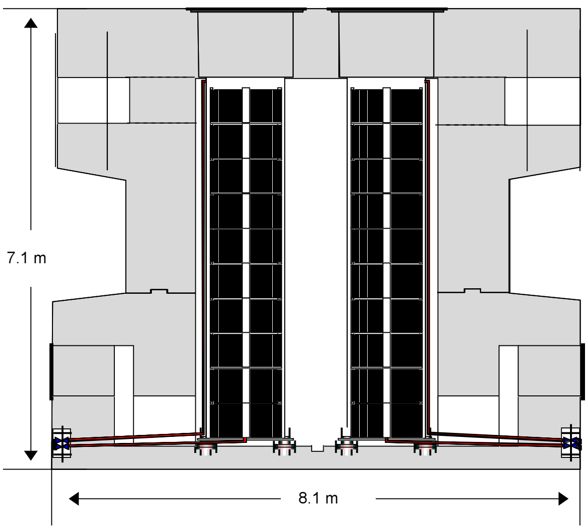

FIG. 2. MACSTOR Dry Storage Module - Gentilly 2

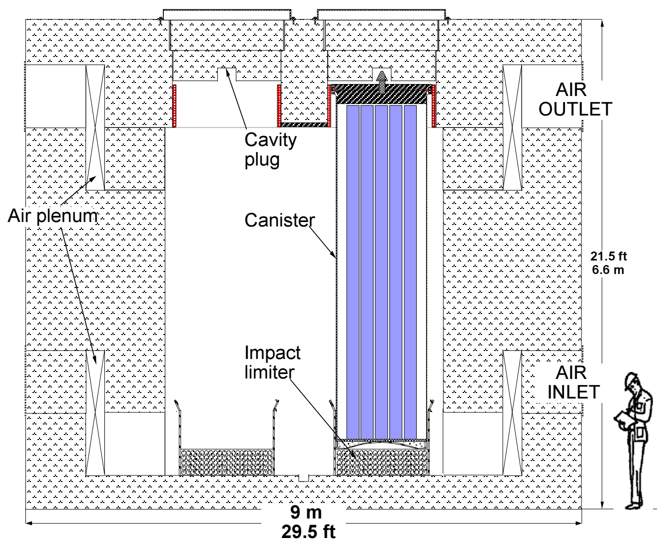

FIG. 3. MACSTOR Dry Storage Module - LWR Configuration

3. DISPOSAL OF CANDU NUCLEAR FUEL WASTE

Current storage practices have an excellent safety record at CANDU sites, permit easy monitoring and retrieval, and could be continued for many years. But storage, while an extremely effective interim measure, is not considered to be a permanent measure. Thus, the objective for permanent disposal is to manage nuclear fuel waste in a way that does not require further intervention, even in the long term, and that, ideally, does not depend on institutional controls to maintain safety. This does not mean that society would not use long-term institutional controls as a management tool, but rather that, even if such controls should fail, human health and the natural environment would still be protected and it does not mean that intervention is precluded but rather that it is not required.

Canada and other countries with mature nuclear power programs have for many years been developing the technology for the permanent disposal of nuclear fuel waste. There is international consensus among waste management experts that the preferred method for long-term management of nuclear fuel waste is land-based geological disposal [4].

Land-based geological disposal would involve placing containers of waste in sediment or rock hundreds of meters deep with access from the land surface. Advantages of land-based geological disposal are that most nations have within their borders rock types potentially suitable for disposal, and land-based disposal concepts can be based on existing mining and engineering technology. Research has concentrated on disposal media (rock types) having one or more of the characteristics commonly considered favorable for disposal. The decision to focus on a particular rock type or types is made in each country on the basis of the geological conditions within that country and a variety of other relevant factors. International research on land-based geological disposal of radioactive waste has concentrated on five disposal media: crystalline rock, salt, clay (or shale), tuff, and basalt.

Canada, like other countries, is basing its plans for disposal of nuclear fuel waste on deep geological disposal, in the Canadian case, in stable crystalline rock of the Canadian Shield. In common with the approach adopted in other countries, the disposal concept developed by AECL, entails isolating the waste from the biosphere by a series of engineered and natural barriers [5]. These barriers include: the waste form itself (either spent fuel or the solidified high level waste from reprocessing); long-lived containers in which the waste is sealed; buffer materials to separate the containers from the surrounding rock and to control the movement of water to, and corrosion products away from, the container; the use of seals and backfill materials to close the various openings, tunnels, shafts, and boreholes; and the rock mass in which the repository is located (the geosphere). The biosphere, although not a barrier per se, is an important part of the overall system. Because it contains the pathways through which direct exposure of humans and other organisms to contaminants could occur, it must be studied as part of any waste management program.

In the Canadian concept, as in most countries, waste would be emplaced in a repository excavated in stable rock below the water table. Hence, the principal concern from the point of view of long-term safety is that groundwater could eventually become contaminated with radioactive or other hazardous materials, and ultimately make its way to the surface and pose a risk to future human health or the environment. The multibarrier system developed for the Canadian concept will prevent this by the combined effects of radioactive decay and the containment, retardation, dispersion and dilution that will take place as contaminants try to move through the disposal system (from the waste form, through the container, buffer, backfill, and geosphere) to the surface such that humans and other organisms will not be exposed to an undue risk. Thus, human health and the environment will be protected.

Considerable efforts have been made internationally to evaluate the behaviour of deep geological repositories with time and their long-term safety. There is an international consensus among waste management experts that "appropriate use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations" [6].

Several countries [7, 8, 9, 10, 11, 12], including Canada [5, 13] have carried out quantitative assessments of the risk associated with disposal. These analyses indicate that the amount of contaminants moving from a repository to the surface would be very small and that the radiological impact would be many orders of magnitude less than that from naturally occurring radioactivity in the surface environment.

4. TECHNICAL AND ECONOMIC ISSUES ASSOCIATED WITH THE DIRECT DISPOSAL OF SPENT CANDU FUEL

A key consideration in assessing the long-term performance of a disposal system is the stability of the waste form, since the waste form contains the radioactive species of concern and it represents the source term for safety and performance assessments. Spent uranium dioxide fuel is an excellent waste form under the reducing groundwater conditions expected at depth in saturated rock. The long-term stability of spent fuel has been assessed in studies of natural analogues such as the Cigar Lake uranium ore deposit [14]. This ore deposit, formed 1.3 billion years ago, has been in contact with groundwater since its formation. Yet the uranium has remained stable and very little dissolution has occurred under the reducing groundwater conditions prevailing in the deposit. Solidified waste from reprocessing is also an excellent waste form, so both spent CANDU fuel and the solidified waste from reprocessing the spent fuel can be safely disposed.

Although the reprocessing of spent fuel to extract useful material for recycling is possible, it is not currently done in Canada, and there are no plans to do so. If spent fuel were reprocessed, almost all the radioactive material that remained (the high-level waste) would be solidified. Reprocessing does not change the quantities of the radionuclides in spent fuel, nor are the total activity and heat generated by the radionuclides. Thus reprocessing in itself would not reduce the amount of fission products, per unit of electricity generated, to be disposed. For the first few hundred years, when the activity is dominated by fission products, the total activity per unit of electricity generated would be roughly the same for vitrified high-level waste as for the spent fuel from which it was derived. Similarly, for the first few hundred years, the rate of heat production would be nearly the same for both types of waste. To meet the thermal constraints for underground disposal, the size of repository required for disposal of the vitrified high-level waste alone would be about the same as for the spent fuel from which it was derived. Therefore, both options-direct disposal of fuel bundles, or disposal of reprocessed, vitrified waste, have similar costs.

For example, Canadian studies of the direct disposal in granite of spent natural uranium CANDU fuel indicate a repository requirement of about 400 to 700 m^2 per TW•h of electricity (Table II) [15, 16]. Swiss studies on the disposal of vitrified reprocessing waste, also in granite, indicate a comparable or somewhat larger repository requirement of about 600-1200 m^2/TW•h [11]. Finnish and Swedish studies for the disposal of used BWR and PWR fuel indicate a similar requirement of about 500-1000 m^2/TW•h [17, 18].

TABLE II. COMPARISON OF SPACE REQUIREMENTS FOR THE DISPOSAL OF HIGH LEVEL WASTE

Country	Waste Form	Burnup of fuel MW•d/Mg(U)	Storage Period Before Disposal (a)	Waste Emplacement Method	Plan† Area of Repository (m^2/TW•h)
Canada	used NU CANDU fuel	7900	10	in boreholes from rooms	400
Canada	used NU CANDU fuel	8300	10	in-room	660
Sweden	used BWR and PWR fuel	35 000 BWR 39 000 PWR	~40	in boreholes from rooms	500
Finland	used BWR fuel	35 000	20 to 40	in boreholes from rooms	500-900
Switzerland	vitrified waste from reprocessing	-		in-room	600-1200

† This figure assumes an ideal geometry. The actual plan area will be larger because rooms will be laid out to avoid important geological features such as fracture zones and faults.

This result comes about because the quantity of heat-generating waste per unit volume of a repository is limited by the maximum acceptable heat load from the waste on the waste container, the repository sealing systems such as clay-based buffer materials, and the surrounding host geological formation. With spent fuel that has been out of the reactor for a given time, the amount of heat the fuel generates depends on the fuel burnup, which normally corresponds to the amount of electricity that was generated by the fuel. Thus, the size of a repository is not a strong function of the volume of the heat generating waste but to a first approximation depends only on the amount of electricity that was generated to produce the waste.

Reprocessing operations also produce streams of low- and intermediate-level waste that contain long-lived radionuclides. Efforts are under way to reduce the volumes of these wastes [19], but nonetheless they represent a waste stream that will need to be disposed of and many countries are basing their plans on using deep geological disposal to isolate these wastes from the biosphere. Direct disposal of CANDU fuel bundles eliminates this need.

The overall cost of deep geological disposal depends not only on the size of the repository, but also on the costs associated with site characterization, the construction of shielded waste handling facilities, supporting research and development, safety assessments, etc., all of which represent more or less fixed costs. These costs do not depend so much on waste volumes and waste forms as on factors such as geological setting, the scale of the nuclear program and details of the system design such as design of the waste container.

These factors, together with the fact that the size of a repository is more a function of the radioactivity and heat produced by the waste rather than its volume means that the costs of disposal (not including the cost of reprocessing) per unit of electricity produced, are comparable for the direct disposal of spent fuel and for the disposal of the long-lived waste that arise from reprocessing.

This broad conclusion is supported by Canadian studies looking at the impact of using enrichment to increase the burnup of CANDU natural uranium (NU) fuel and hence to reduce the volume of spent fuel to be disposed [20].

It is estimated that increasing the burnup by up to a factor of four, and hence reducing the volume of spent fuel for a given total production of electricity by about a factor of four, would, for a given design of repository, not change the total cost of disposal by more than 5 or 10%. The higher heat load from the spent slightly enriched uranium (SEU) fuel offsets the cost reductions that might be expected to occur from the smaller volume of spent fuel. In fact, as enrichment and hence the heat load increase, costs of disposal eventually begin to rise, unless the spent fuel is first stored for an extended period before disposal (Fig. 4).

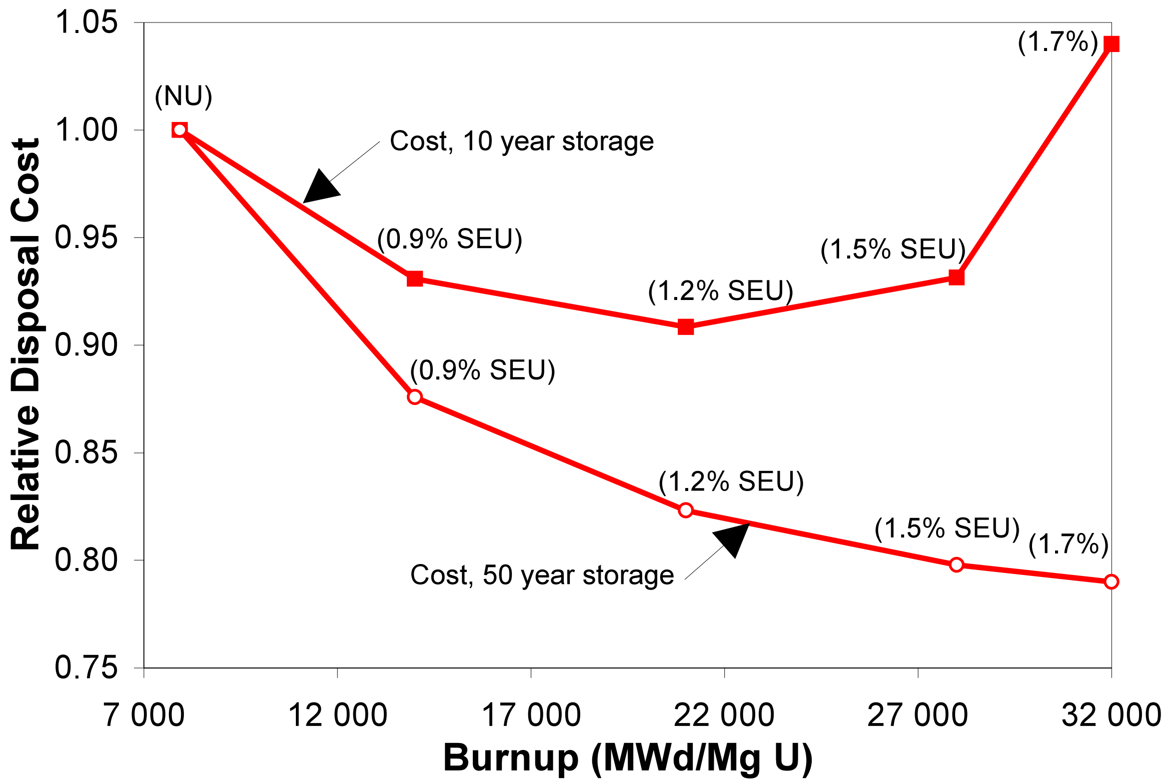

FIG. 4. Relative (Total disposal) Costs as a Function of Burnup (Enrichment) for the Direct Disposal of Spent CANDU Fuel Using Borehole Emplacement of Waste Containers in a Repository Excavated in Crystalline rock of the Canadian shield for a Fixed Generation of 4300 TW.h of Electricity.

If the spent enriched fuel is stored for a period of say 50 years before disposal, compared with a reference time used in most studies of 10 years, total disposal costs could be reduced up to 20% or so, compared with disposal of 10-year old spent natural uranium fuel, for a fixed amount of electricity generated. The direct cost component for disposal reduces by up to ~30% or so when the fixed costs of siting and R&D are removed.

The estimated costs for disposing of different forms of high-level waste – direct disposal of spent CANDU and spent LWR fuels and the disposal of reprocessing wastes (not including the costs of reprocessing) – have been compared [17]. This comparison shows that the estimated costs for the direct disposal of spent CANDU fuel, for a given production of electricity are comparable or less than for the direct disposal of other waste forms (both spent LWR fuel and reprocessing wastes). Differences in estimated costs are more related to factors other than the waste form, factors such as the host geology, whether or not an overpack is used and the size of the national nuclear program. Typical results are shown in Fig. 5.

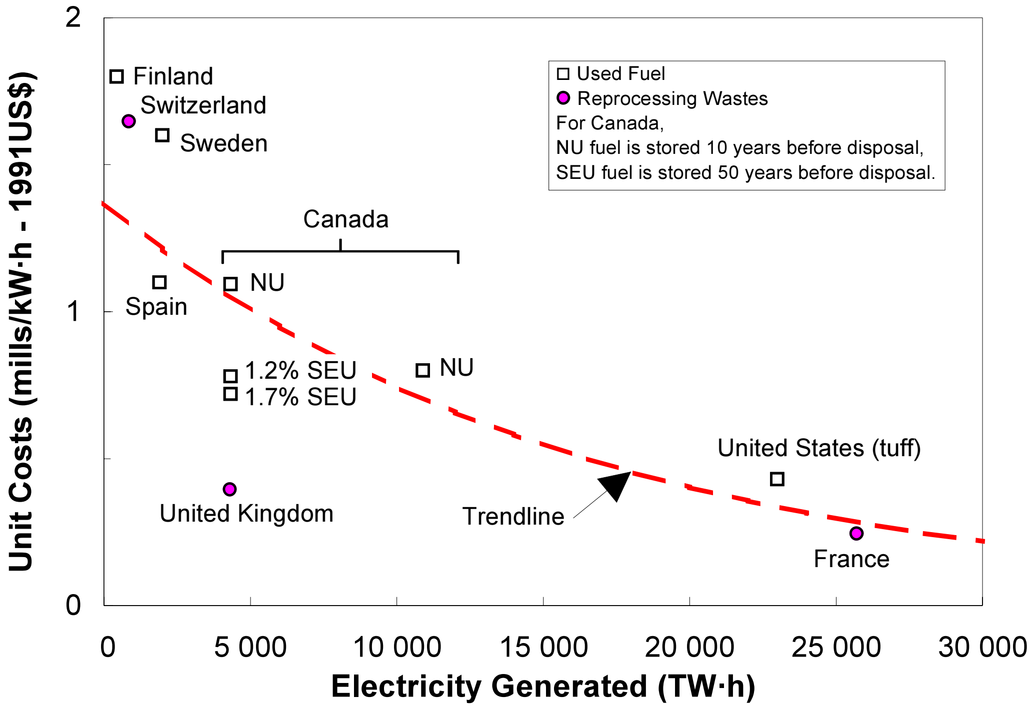

FIG. 5. Costs of Packaging and Disposing of Nuclear Fuel as a Function of Generated Electricity.

(Costs do not include the costs of site screening, site evaluations, and supporting R&D. Data are taken from Ref. [17] supplemented with additional results from Canada Ref. [20] for disposal of used SEU CANDU fuel. Except for France and the U.S.A., costs are for disposal in crystalline rock. No host rock is specified for France because different geological media have been considered in the estimates.)

5. CONCLUSIONS

In summary, the CANDU 6 design is backed by well-established, safe and economical means of short- and medium-term storage, and by more than 20 years' experience at AECL in defining and proving concepts for permanent disposal. Natural uranium CANDU fuel has the advantage that concerns about fuel criticality are eliminated in both wet and dry storage. Further, CANDU spent fuel storage baskets can be moved directly from pool storage to dry storage facilities. CANDU spent-fuel dry storage costs are estimated to be lower than for PWRs based on current studies, partly as a consequence of the more easily-handled CANDU fuel bundles. For permanent disposal, the Canadian program to develop a technically acceptable disposal concept provides an international demonstration of feasibility. It also establishes well-supported cost benchmarks, showing that permanent disposal costs for CANDU fuel would be comparable with costs for PWRs.

REFERENCES

[1] FROST, C.R., Current Interim Used Fuel Storage Practice in Canada, Ontario Hydro Nuclear Report, N-03710-940052, Toronto (1994).

[2] PARÉ, F., Dry spent fuel storage with the MACSTOR system, Proceedings of the 10th Pacific Basin Nuclear Conference, Vol.2, Kobe, Japan, (20-25 October 1996) 1081pp.

[3] BEAUDOIN, R.R., PATTANTYUS, P., Comparison of dry fuel storage costs and required land area for CANDU 9 and Light Water Reactors (LWRs) in South Korea, Appendix B in Atomic Energy of Canada Limited Report, AECL-11892, Ottawa (1997) 41-48 pp.

[4] ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD), The Environmental and Ethical Basis of Geological Disposal of Long-lived Radioactive

Wastes- A Collective Opinion of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency, Paris (1995).
[5] ATOMIC ENERGY OF CANDA LIMITED, Environmental Impact Statement (EIS) on the Concept for Disposal of Canada's Nuclear Fuel Waste, Atomic Energy of Canada Limited Report, AECL-10711, COG-93-1, Ottawa (1994).
[6] ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD), Disposal of Radioactive Waste: Can Long-Term Safety be Evaluated? An International Collective Opinion, OECD/NEA, Paris (1991).
[7] NUCLEAR FUEL SAFETY PROJECT- KBS, Final Storage of Spent Fuel-KBS-3, SKBF/KBS Report, ISSN 0349-6015, Stockholm (1983).
[8] NATIONAL COOPERATIVE FOR THE DIPOSAL OF RADIOACTIVE WASTE (NAGRA), Project Gewahr, Nuclear Waste Management in Switzerland: Feasibility Studies and Safety Assessment, Nagra Project Report, NGB-85-09E, Wettingen, Switzerland (1985).
[9] NUCLEAR FUEL AND WASTE COMPANY (SKB) '91, Final Disposal of Spent Nuclear Fuel: Importance of the Bedrock for Safety, SKB Technical Report 92-20, Stockholm (1992).
[10] VIENO, T., HAUTOJÄRVI, A., KOSKINEN, L., NORDMAN, H., TVO-92 Safety Analysis of Spent Fuel Disposal- YJT Technical Report, YJT-92-33E, Finland (1992).
[11] NATIONAL COOPERATIVE FOR THE DISPOSAL OF RADIOACTIVE WASTE (NAGRA), Kristallin-I Safety Assessment Report, Nagra Technical Report, NTB 93-22, Wettingen, Switzerland (1994).
[12] POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION (PNC), "Research and Development on Geological Disposal of High-Level Radioactive Waste, First Progress Report," PNC Report, PNC TN1410 93-059, Chapter 4, Japan (1992).
[13] 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-95-522-1, Ottawa (1996).
[14] CRAMER, J., "The Cigar Lake Uranium Deposit: Analog Information for Canada's Nuclear Fuel Waste Disposal Concept," Atomic Energy of Canada Limited, Report AECL-11204, COG-94-524, Ottawa (1995).
[15] SIMMONS, G.R., BAUMGARTNER, P., The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility, Atomic Energy of Canada Limited, Report AECL-10715, COG-93-5, Ottawa (1994).
[16] BAUMGARTNER, P., et al., Engineering for a Disposal Facility Using the In-Room Emplacement Method, Atomic Energy of Canada Limited, Report AECL-11595, COG-96 223, Ottawa (1996).
[17] ORGANIZATION FOR ECONOMIC DEVELOPMENT AND CO-OPERATION/NUCLEAR ENERGY AGENCY (OECD/NEA), The Cost of High-Level Waste Disposal in Geological Repositories. An Analysis of Factors Affecting Cost Estimates, OECD/NEA, Paris, 1993.
[18] AGESKOG, L., SJODIN, K., Tentative Outline and Siting of a Repository for Spent Nuclear Fuel at the Finnsjon Site, SKB Technical Report, SKB 91-36,Stockholm (1991).
[19] **"Not A Lot of Waste,"** ***Nuclear Issues*****, <u>16</u>(4), 4, 1994. (INCOMPLETE)**
[20] ALLAN,C.J., BAUMGARTNER, P., "Back-end of the Nuclear Fuel Cycle: A Comparison of the Direct Disposal and Reprocessing Options," Proceedings of the 10th Pacific Basin Nuclear Conference, Vol. 1, Kobe, Japan (20-25 October 1996) 51pp.