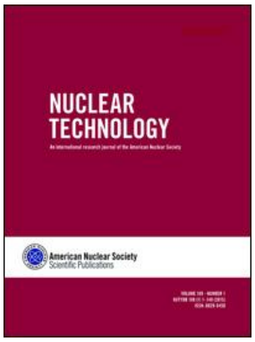

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THE MANAGEMENT OF SPENT CANDU FUEL

RADIOACTIVE WASTE

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KEYWORDS: *CANDU reactor, radioactive waste management, radioactive waste storage, planning, radioactive waste disposal, cost*

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Projections have been made regarding the quantities of spent fuel arising from reactors in Canada. It is concluded that for at least 75 years the waste will be manageable and the storage risk is acceptably small.

Conceptual designs of several fuel storage facilities have been completed and fuel storage costs were estimated. These are in the region of 0.1 mil/kWh for all storage schemes studied.

A choice of the specific interim storage facility to be used has not yet been made. However, it is believed that any of the systems described would be acceptable.

INTRODUCTION

Fueling costs in CANDU reactors are low.[1] For this reason, reprocessing of fuel will be delayed until necessary and, if sufficient resources were available, it could be avoided completely. The options are shown in Fig. 1.

In the current fuel cycle, natural uranium fuel is fed into the reactors, and spent fuel is the waste product. There are three options at this point. The fuel can be stored, sent to disposal, or reprocessed. Since at the present time new fuel costs, storage costs, and spent fuel values are all low,[2] it is not likely that an early decision will be forthcoming. Furthermore, the Atomic Energy Control Board guidelines in Canada allow for retrievable storage of fuel on an interim basis. Thus, for some time to come, Canadian spent fuel will be stored in a retrievable fashion in engineered vaults. The object of this paper is to assess the size of this operation and to discuss some of the engineered structures which could be used.

THE "WASTES" TO BE STORED

A CANDU fuel bundle is shown in Fig. 2. This is a convenient package for waste storage, at least on an interim basis. As is well known, Zircaloy is corrosion resistant in both air and water up to at least 300°C (Refs. 3 and 4). In either of these media, the sheath should provide a containment barrier for a minimum of 100 years, which is sufficient time to allow for a considerable decay of fission products. Also, the fuel has survived about two years of reactor service, which is much more demanding than storage conditions. It seems reasonable, therefore, to store the spent bundles as ejected from the reactor. Since the interim storage period will in all probability be much less than 100 years, there is good reason to believe that sheath containment alone will be sufficient for most storage techniques. However, in practice, one or two additional barriers will be used to ensure containment.

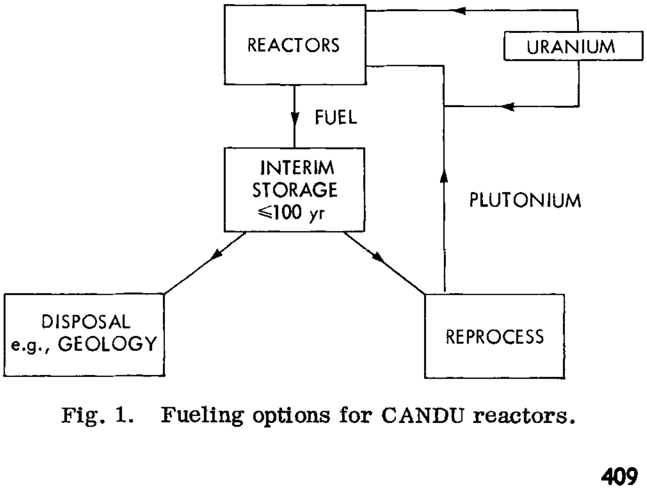

Fig. 1. Fueling options for CANDU reactors.

THE SIZE OF THE PROBLEM

Projections of spent fuel arisings have been made, and these are shown in Table I. The values are based on upper limit estimates of population growth and energy consumption. The assumptions made are as follows:

1. The present rate of population growth continues to the year 2050, followed by a rate decrease to zero over the next 50 years.
2. The present rate of increase in power consumption continues to the year 2000, followed by a rate decrease to zero over the next 50 years.
3. Equilibrium power usage is 50 kW(th) per capita.
4. Nuclear power supplies 100% of the energy requirement by the year 2060.

This should represent an extreme upper limit for Canada. For example, it leads to an equilibrium population of 190 million, about a factor of 10 increase over the present day. However, the accuracy of this projection is not very important. The object is to decide if the expected upper limit leads to spent fuel arisings which are manageable for the indefinite future. As will be shown, this is indeed the case.

Table I shows that in the year 2000, 100 000 MT of spent fuel will have accumulated, containing 3×10^{10} Ci of activity, with a decay heat of 80 MW. This is a minor storage problem when viewed in the proper perspective. For example, the fuel could be contained in about ten pools, each having a surface area of ~4000 m^2. The total activity is comparable to that contained in an operating 1000 MW(e) reactor. Thus, the accumulated fuel need not be contained to a higher degree. The last two columns in the table compare the water toxicities of the storage repository and the operating reactors. In general, the toxicity of the repository contents is about a factor of 10 less. Thus, if all spent fuel were stored on the reactor site, the risk for the whole site would only

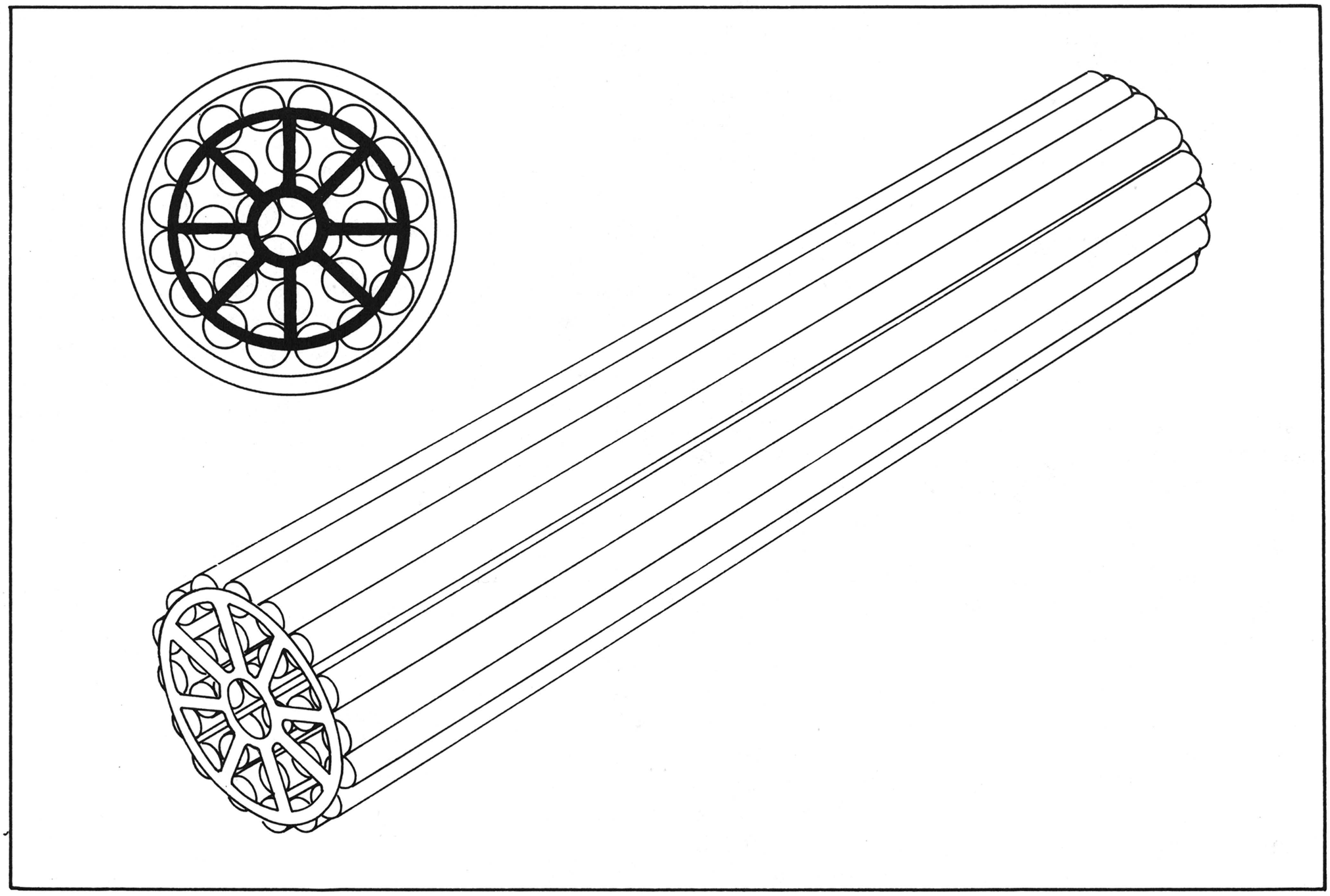

Fig. 2. CANDU fuel bundle.

increase by ~10%. Since we believe the risk from operating the reactors is small, the site risk must also be small, provided the stored fuel is contained at least as well as the fuel in the reactor.

The bottom line in Table I shows a projection for the year 2050. This is only a best guess but is probably correct within a factor of 10. Assuming that fission reactors with the present fuel cycle are viable over this time scale, Canada would have irradiated 4×10^6 MT of uranium by 2050. This is about a factor of 10 higher than Canada's present reasonably assured resources recoverable at a cost of <$15/lb, but the supply of this quantity is not beyond the realm of possibility.

TABLE I

Projections for the Canadian Nuclear Power Program

Year	Installed Nuclear Capacity [GW(e)]	Cumulative Mass of Spent Fuel ($\text{MTU} \times 10^{-3}$)	Repository Activity ($\text{Ci} \times 10^{-9}$)	Repository Decay Heat [MW(th)]	Toxicity[a] in Reactor (m^3 of H_2O)	Toxicity[a] in Repository (m^3 of H_2O)
1975	2.5	0.6	---	---	7×10^{14}	4×10^{13}
1980	6.9	3.4	2	4	2×10^{15}	2×10^{14}
1985	18	10	---	---	5×10^{15}	5×10^{14}
1990	40	22	20	25	1×10^{16}	1×10^{15}
1995	78	50	---	---	2×10^{16}	3×10^{15}
2000	138	100	30	80	4×10^{16}	5×10^{15}
2050	2500	4000	800	2000	7×10^{17}	2×10^{17}

[a] The water dilution required to meet the International Commission on Radiological Protection (ICRP) specification for the public.

TABLE II

Comparison of Fuel Storage Schemes

	Water Cooling	Air Cooling			Heat Sink Cooling
	Pools	Conduction Vault	Convection Vault	Canister	Salt Mine
Advantages	high storage concentration ease of access flexible developed	high storage concentration no secondary wastes reliable cooling	high storage concentration no secondary wastes reliable cooling	simple no secondary wastes reliable cooling	simple no secondary wastes reliable cooling long diffusion path to biosphere
Disadvantages	vulnerable to political instability secondary wastes generated high performance cooling required long-term corrosion	vulnerable to political instability uses scarce resources relatively high structural temperatures	vulnerable to political instability uses scarce resources cooling air passes through vault	vulnerable to political instability large number required may be difficult to monitor	difficult to monitor fuel may be difficult to retrieve

The table also shows that the total activity stored is about a factor of 30 higher than in 2000. However, it should be noted that the activity of the fuel stored in the repositories is beginning to approach a limit because the decay rate approximates the addition rate. If we assume 10 major nuclear sites exist in 2050, then about 400 000 MT of fuel will be stored at each location. If this is stored in pools containing 10^4 MT each, then only 40 pools would exist at each site. Therefore, the quantity of wastes seems manageable and the degree of risk acceptably small.

This type of storage is not a long-term solution. For example, the plutonium and other actinide materials contained in spent fuel require containment for periods approaching 10^6 years. Similarly, the fission products require containment times of 10^3 years or longer. However, in the absence of a world concensus regarding storage philosophy, engineered vaults may be used for an interim period. It seems clear than spent fuel could be stored in Canada for at least the next 75 years with little or no increased risk to the existing reactor sites. Furthermore, the scale of operations is such that only minimal management operations would be anticipated.

INTERIM STORAGE METHODS

A conceptual design study has recently been completed on some of the methods which could be used to store spent fuel on an interim basis. This is a preliminary study and further work is required before a particular vault is chosen as the reference storage scheme. Vault designs were based on water, air, and heat sink cooling. Advantages and disadvantages of each scheme are listed in Table II. Schematic drawings of each are shown in Figs. 3 through 8. The main effort of the study was directed toward costs and concepts used in fuel handling. Obvious accidental occurrences such as loss of cooling were considered, but an in-depth safety analysis remains to be completed.

Water Cooling

The only water-cooled schemes studied in any detail were pools. Since these are familiar, no

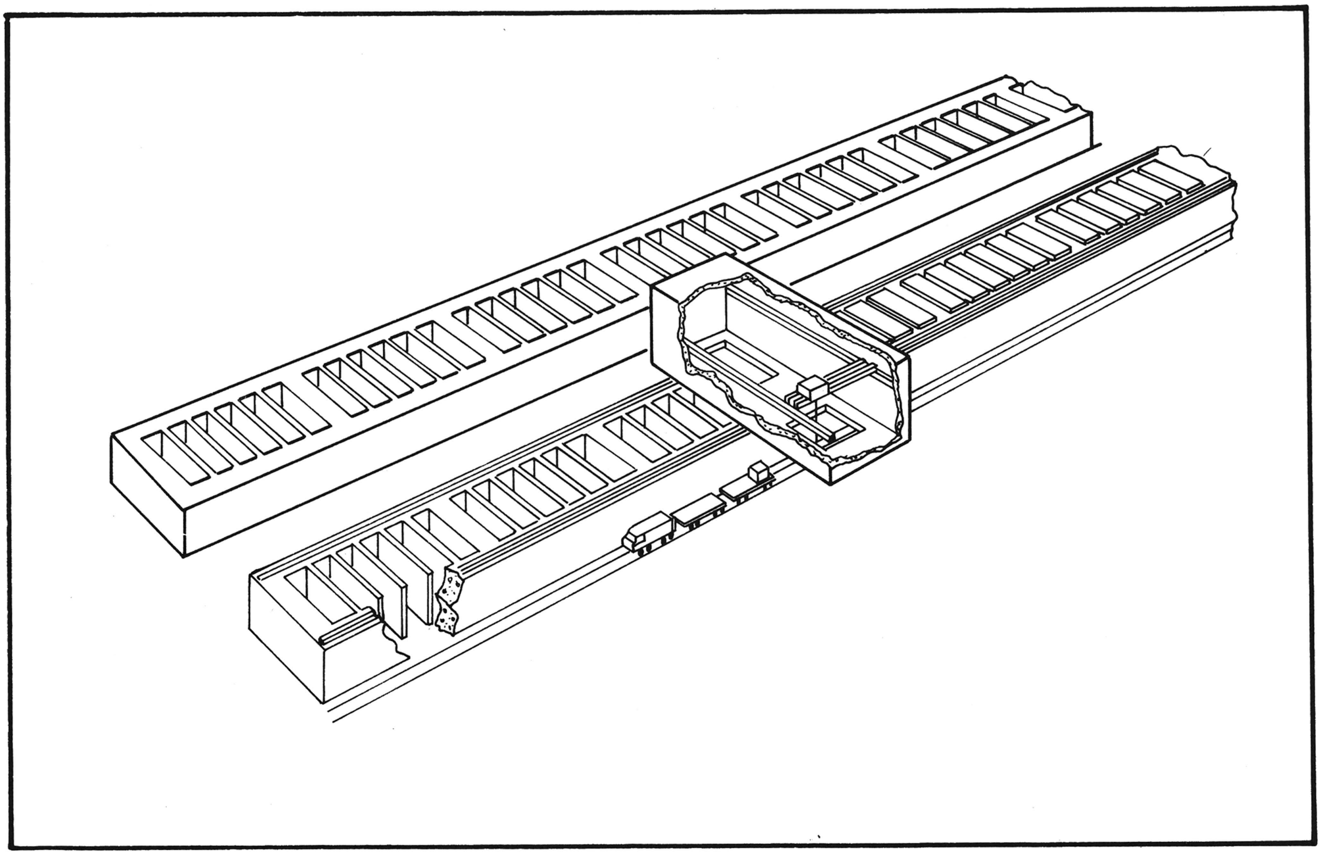

Fig. 3. Storage pool.

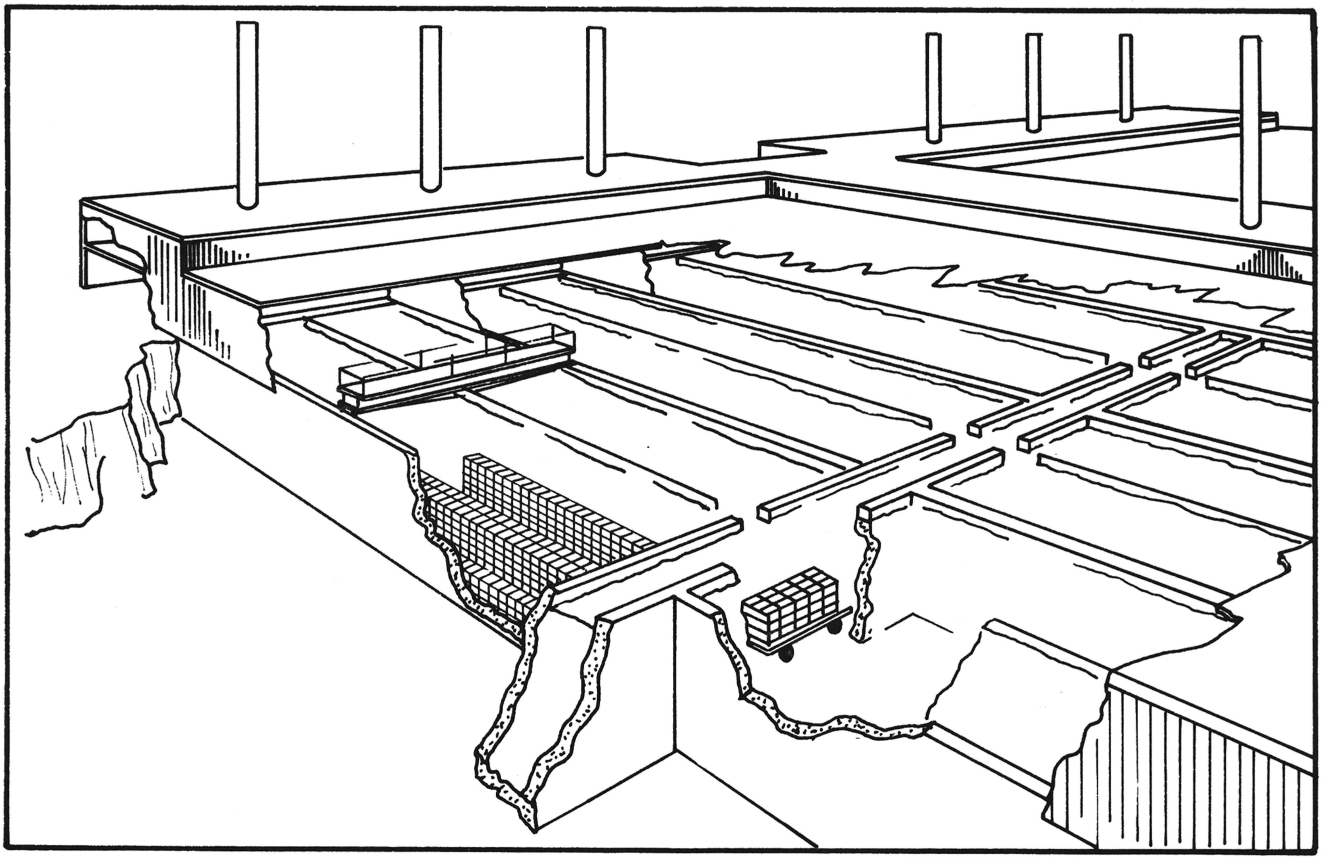

Fig. 4. Storage pool.

description of the facilities is necessary. As shown in Figs. 3 and 4, two types which vary slightly in design were examined. In addition, cost estimates were based on the assumption that one set of pools (Fig. 3) would be sited with the reactor and the other set (Fig. 4) would be at a central storage site.

Some of the ground rules taken for the design are as follows:

1. Fuel bundles are not canned prior to storage.
2. Facilities exist for the detection of fuel failures.
3. Pool water is continuously polished by filtration and ion exchange.
4. Primary and secondary cooling circuits are used.
5. Emergency water and power supplies are available.
6. Excess storage capacity is included.

The major conclusions were as follows:

1. Corrosion and fuel failure wastes should not be a problem.
2. Off-site discharges should be very low.
3. The major nuclear problem will be the man-rem expenditure during flask handling. This could be the major problem associated with all storage schemes. However, it should be controllable with good flask design.
4. Operating costs will be high in comparison with dry storage techniques.

Air-Cooled Vaults

Canisters

One of the simplest methods of storing spent fuel is to contain it in a flask and rely on natural convection air cooling. The facility chosen for study is shown in Fig. 5. The fuel bundles are sealed in a steel container at the reactor site and transported to a central storage site, where they are placed in a canister. An array of canisters would be placed in a supervised field. The canister shown in Fig. 5 is fabricated from reinforced concrete, but steel could be used if desired. With a concrete canister, 4.4 MT of

CANDU fuel, precooled for 5 years, goes in one package. Larger packages would lead to excessive fuel sheath temperatures. However, if larger packages are desirable, they could be achieved by using metal canisters and/or filling the fuel bundle voids with a heat transfer medium.

The advantages of this concept are its simplicity, low operating costs, and lack of dependence on mechanical equipment. For example, it is difficult to imagine a loss-of-coolant accident. The major disadvantage is the large number of containers required. About 23 000 of the canisters shown here would be required up to the year 2000. However, they will only occupy a few hundred acres, which is small in comparison with areas used for generating sites and power line rights-of-way.

Conduction and Convection Vaults

Two other types of air-cooled vaults were considered and named the "conduction" and "convection" vaults. These are outlined schematically in Figs. 7 and 8. Since direct contact air cooling by natural convection is required in the convection vault, extra containment of the fuel was considered essential. Also, the conduction vault requires a heat transfer medium. Both purposes are served by the casting process illustrated in Fig. 6 and described below.

Six fuel bundles are placed in a trefoil-shaped aluminum pipe. This pipe shape was chosen to maximize surface area and to minimize metal costs and strains during cooling. Molten zinc or aluminum is poured into the pipe. The required charge of casting metal is added until the bundles are totally immersed. The result is a strong, well-contained package with good heat transfer properties. Six of the casting modules are packed into a rack or basket which is shipped to the storage site.

In the convection vault, the casting modules are stacked as shown in Fig. 8. At the appropriate lattice pitch and stack height, natural draft cooling is achieved. A chimney was not considered in the design, nor was absolute filtration of the effluent

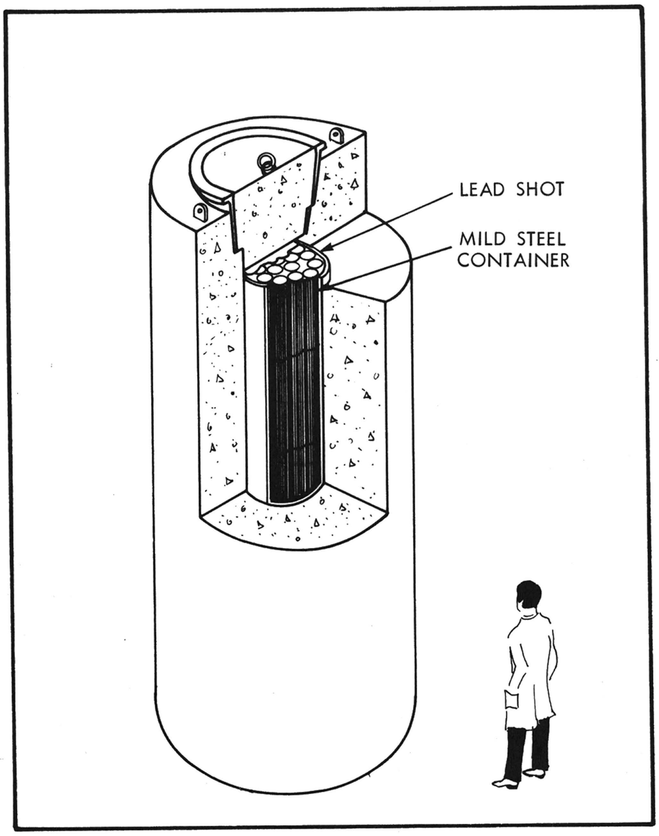

Fig. 5. Canister.

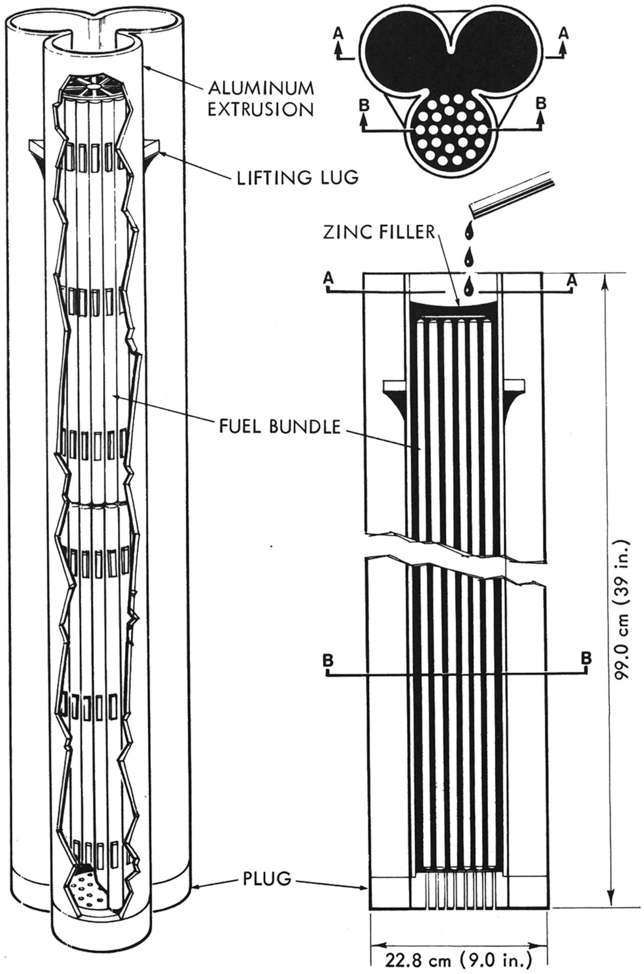

Fig. 6. Casting module.

air. Instead, the designers relied on the containment of the fuel sheath and casting metal to prevent possible air entrainment of activity. However, forced air circulation with filtration could be used if experience shows this to be necessary.

A schematic drawing of the conduction vault is shown in Fig. 7. The casting modules are stacked as before, but the height is limited because the metal matrix must transfer all heat by conduction. Thus, each stack is hottest at the bottom. A shielding plug with cooling fins is placed on top of each stack and cooling is again achieved by natural convection. However, in this vault, cooling air does not directly contact the casting modules. Thus, suspension of activity in the air is less probable than for the convection vault.

In both vaults, the advantages of compact storage and natural convection cooling are obtained. Thus, relatively small repositories result even when all arisings for the next 50 to 100 years are considered. Loss-of-coolant accidents are always a possibility, but the probability can be made very small by proper design.

Geologic Emplacement

Canada does not currently have a program directed toward the emplacement of spent fuel in geologic formations. Nevertheless, a cost estimate for a geologic technique was considered essential for comparative purposes. Since the salt concept is by far the most developed, it was decided to adapt the excellent work of Oak Ridge National Laboratory to our ground rules and type

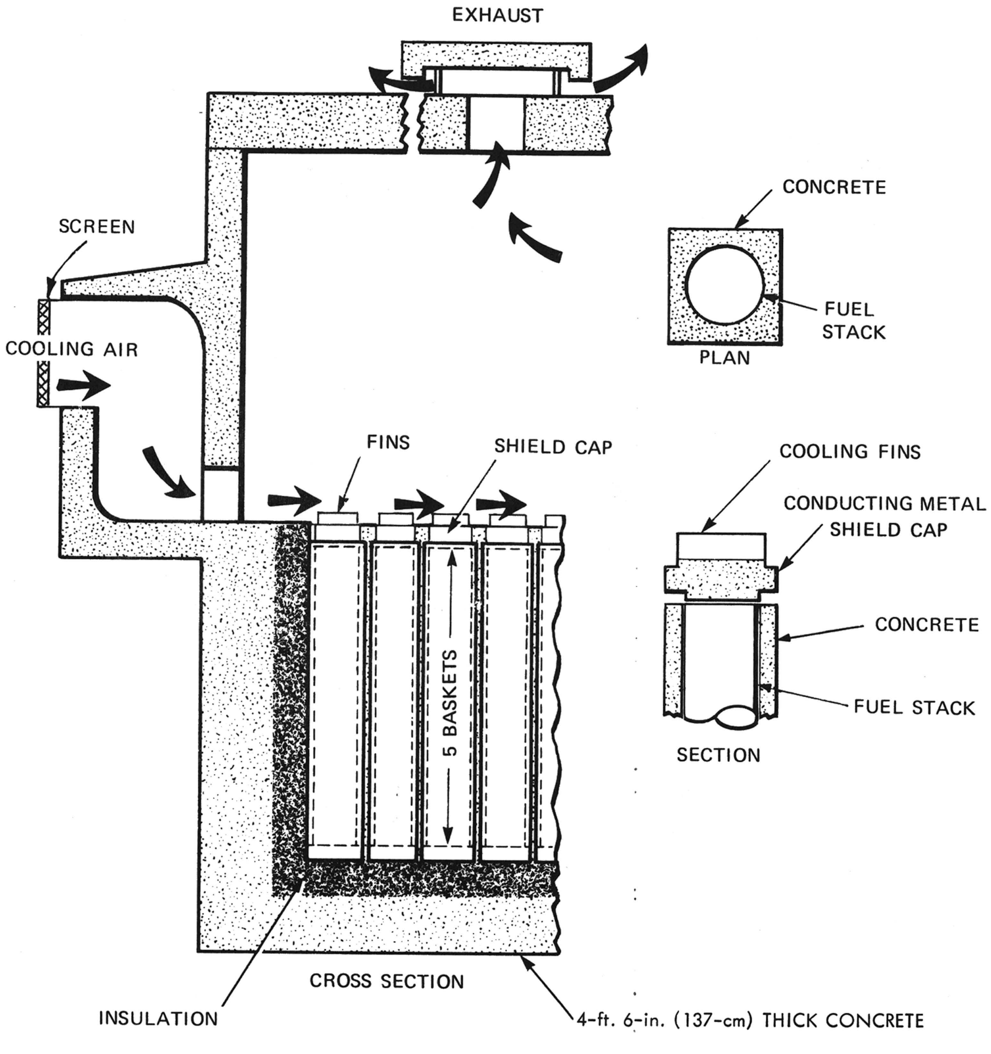

Fig. 7. Dry storage facility—conduction cooling.

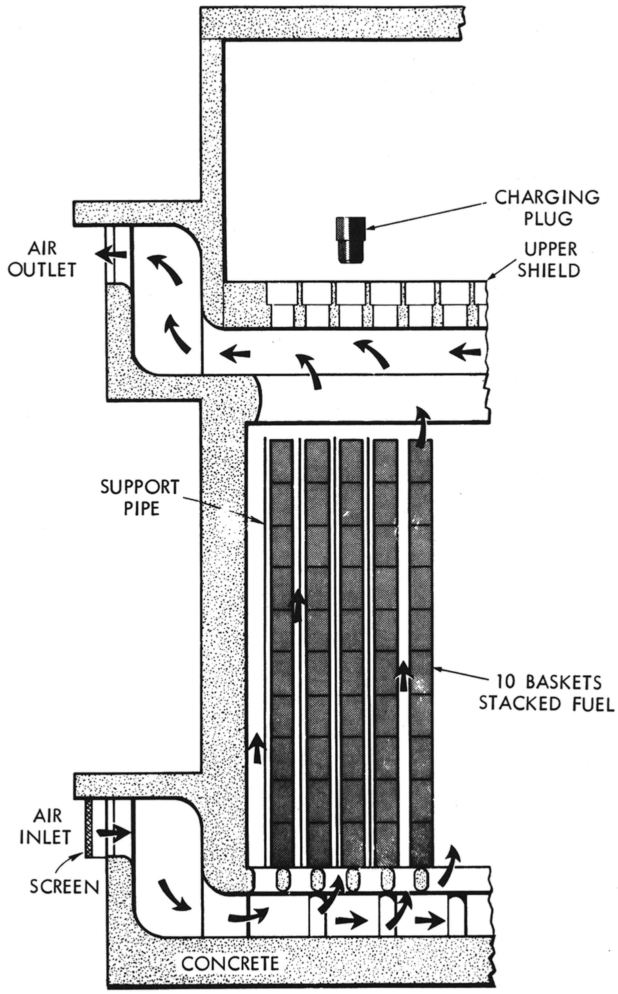

Fig. 8. Dry storage facility– convection cooling.

of packaging.[5] In addition, costs were based on the assumption that the mine must be kept open for 50 years so that the fuel can be easily retrieved during this period. In the opinion of mining consultants, this is a reasonable expectation since heat generation rates are about a factor of 3 to 5 below the expected values mentioned in the literature.[6]

Using conservative criteria, about one square mile of salt is required to contain all fuel generated in Canada up to the year 2000. The fuel is packaged in steel containers at the reactor site and placed in asbestos cement sleeves in the mine floor. A concrete plug is placed on top for shielding. It is anticipated that the fuel could be protected from the salt, and thus be retrievable for 50 years.

The reported major advantages of geologic concepts are that cooling, shielding, and containment are guaranteed. However, although there is an obvious attraction to geology for actinide-containing wastes, and geologic disposal techniques must certainly be considered if the fuel is declared waste, the problems that could arise in retrieval tend to make geologic strata less attractive for interim storage.

COSTS

Costs for the concepts studied are shown in Table III. It should be appreciated that the values are the result of conceptual design studies and are probably accurate only to within ±25%. Also, it is not likely that the difference between the highest and lowest estimates is significant. The obvious overall conclusion that spent fuel management is not a major cost factor in nuclear power has been stated many times. Costs two to three times the values shown could easily be tolerated.

A few other comments can be made. First, these costs are generally higher than values previously reported for light-water-reactor fuels.[7] However, fuel is being considered here, and the volume to be stored is greater than would arise from solidified wastes from reprocessing. Secondly, dry storage techniques lead to much lower

TABLE III

Total Costs for Spent Fuel Management

[mil/kWh(e) based on 1972 Canadian dollars]

	Pools at Central Site	Pools at Reactor Site	Convection Vault	Conduction Vault	Canisters	Salt Mines
Capital and operating costs during filling period	0.049	0.062	0.039	0.049	0.053	0.061
Shipping	0.035	---	0.035	0.035	0.035	0.035
Perpetual care	0.046	0.028	0.008	0.008	0.011	0.003
Total	0.13	0.08	0.08	0.09	0.10	0.10

perpetual care costs. Again, this is to be expected since with pool storage, secondary wastes occur and fairly careful supervision is required. Therefore, there are significant operating costs during the dead period and substantial payments must be made to the perpetual care fund during the filling period to cover these operating costs. Finally, note that the costs are considered to be all-inclusive since they include items such as escalation, working capital, and all capital and operating costs required for the filling and dead storage periods.

CONCLUSIONS

The quantity of spent fuel arising from Canadian reactors is not expected to be difficult to manage for the foreseeable future, even if the use of nuclear power in Canada increases at the maximum credible rate. In addition, the risk associated with storage of this fuel is acceptably low. Any one of the facilities described should be suitable for this purpose. Subsequent work may show that one will be marginally safer than the others, but the probability of a loss of containment will always be extremely small.

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