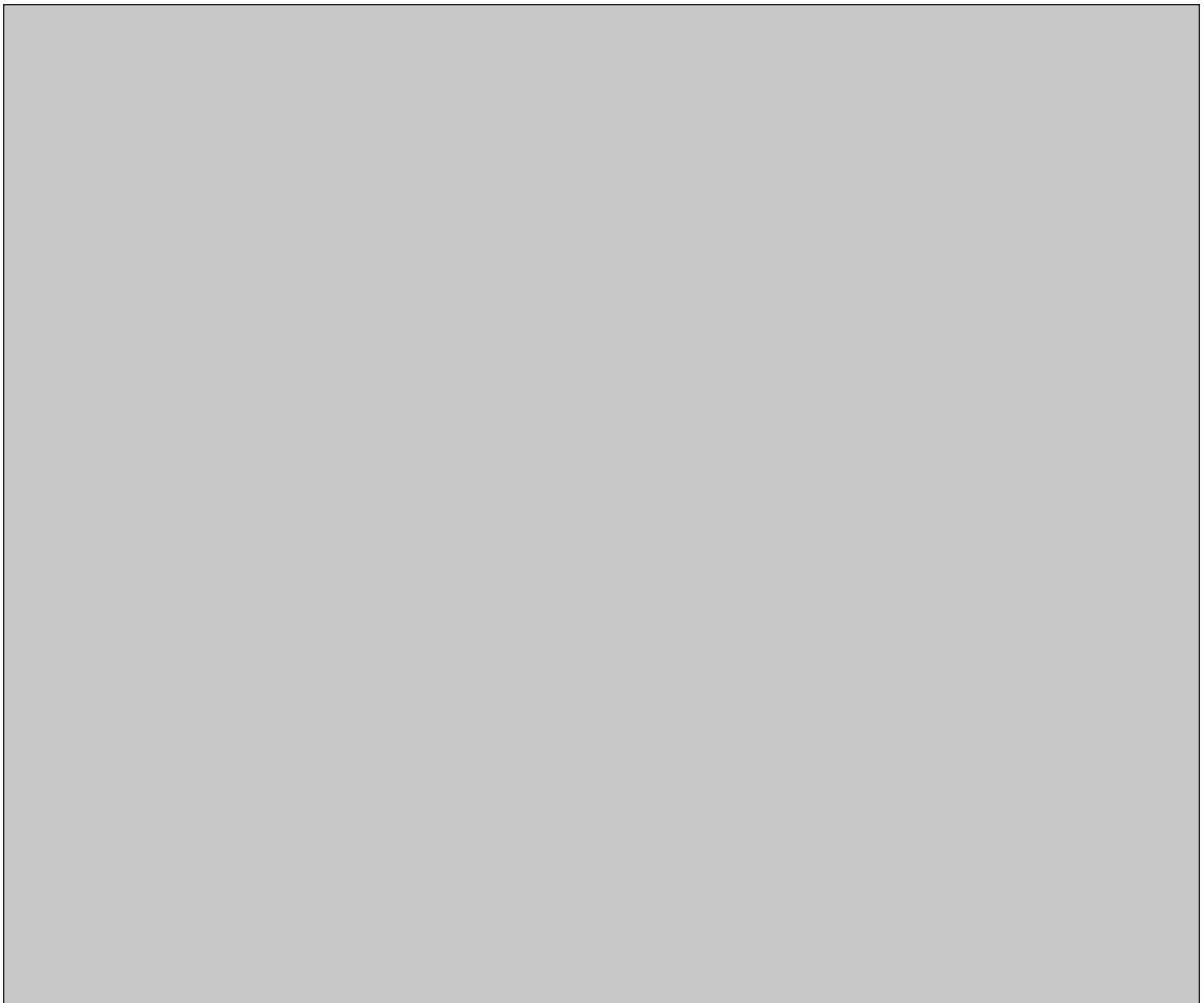# nwmo

NWMO BACKGROUND PAPERS
6.   TECHNICAL METHODS

6-7   STATUS OF STORAGE, DISPOSAL AND TRANSPORTATION CONTAINERS FOR THE MANAGEMENT OF USED NUCLEAR FUEL

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NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts** – describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.

2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.

3. **Health and Safety** – provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.

4. **Science and Environment** – provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.

5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.

6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.

7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

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ACRONYMS

AECL	Atomic Energy of Canada Limited
AGR	Advanced Gas Cooled Reactor
ALARA	As Low as Reasonably Achievable
BWR	Boiling Water Reactor
CANDU	Canada Deuterium Uranium
CESF	Centralised Extended Storage Facility
CNSC	Canadian Nuclear Safety Commission
CRC	Casks in Rock Caverns
CSB	Casks in Storage Buildings
CST	Casks in Shallow Trenches
CVSB	Casks and Vaults in Storage Buildings
CVST	Casks and Vaults in Shallow Trenches
DSC	Dry Storage Container
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IFTC	Irradiated Fuel Transportation Container
ILW	Intermediate Level Waste
LLW	Low Level Waste
LWR	Light Water Reactor
MACSTOR	Modular Air Cooled Canister Storage
MVDS	Modular Vault Dry Store
NFWA	Nuclear Fuel Waste Act
NWMO	Nuclear Waste Management Organization
OFP	Oxygen-Free Phosphorus-doped
OPG	Ontario Power Generation
PWR	Pressurised Water Reactor
RESF	Reactor Site Extended Storage Facility
SMV	Surface Modular Vault
TPRM	Transport Packaging of Radioactive Materials
VSC	Ventilated Storage Cask

BACKGROUND PAPER ON THE STATUS OF
STORAGE, DISPOSAL AND TRANSPORTATION CONTAINERS
FOR THE MANAGEMENT OF USED NUCLEAR FUEL

SUMMARY

The Nuclear Waste Management Organization (NWMO) is mandated to examine a range of approaches for the long-term management of Canadian used nuclear fuel. The principal approaches to be examined are 1) extended storage at reactor sites, 2) extended storage at a central site and 3) geologic disposal. This paper has been prepared at the request of NWMO to present a factual description of the current status of storage, disposal and transportation containers for the long-term management of used fuel.

Following discharge from nuclear reactors, used fuel is stored in water-filled pools to cool it and to provide shielding from its radiation. As pool storage capacity at various sites is becoming full, older and, therefore, cooler used fuel is being transferred to dry storage systems. Dry storage capacity is less expensive and provides a more easily monitored storage system for used fuel. Depending upon the type of fuel and the design of the dry storage units, the fuel must be cooled for periods of up to 10 years before it can be transferred into dry storage. Presently, the total world-wide storage capacity for used fuel is approximately 255,000 megagrams with dry storage representing 17% of this capacity. Both wet and dry storage technologies are considered to be safe and mature technologies, which can provide adequate interim storage for at least 50 years.

The concept of extended storage is one of storage in 'perpetuity'. Wet storage is not a preferred option for extended storage because of its higher maintenance requirements, need for greater monitoring and higher overall cost. While it is feasible to increase the design life of current dry storage structures, it is nevertheless considered that over an extended storage period, used fuel would need to be periodically repackaged into new storage structures. A number of extended storage concepts have been examined for both centralized and reactor site storage. These concepts include both above ground and below ground facilities. These concepts envision storing the used fuel within dry storage containers and/or inside vaults. Extended storage at the reactor site may be a continuation of the current dry storage practice.

In general, extended storage containers must provide safe containment of the used fuel from the time of loading through handling, transportation, emplacement and during storage. Three main types of dry storage systems are currently in use: 1) concrete vaults, which are large ventilated buildings and hold 600-2000 Mg fuel, 2) concrete containers and silos, which hold 5-15 Mg fuel, and 3) metal containers, which hold 10-17 Mg fuel. For dry storage of used fuel in Canada, vaults are used at Gentilly-2, silos are used at Point Lepreau and transportable, rectangular, concrete, dry storage container (DSC)s are used at Ontario Power Generation (OPG) sites. The Pickering DSC can accommodate four fuel modules (a module is a rectangular fuel storage framework used at OPG sites which can accommodate 96 fuel bundles) weighing 10 Mg in total. OPG's design differs significantly from container designs for light water reactor (LWR) fuel; containers for LWR fuel have a cylindrical configuration. Such a configuration is not optimal for CANDU fuel because the CANDU fuel bundles have a much shorter length.

The Canadian used fuel will eventually need to be permanently managed. Geological disposal within the stable granitic rock of the Canadian Shield, at a depth of 500-1000 m, is considered to be generally acceptable for the permanent isolation of the used fuel. The reference Canadian used fuel container has a design life exceeding 100,000 years and has a capacity of 324 used fuel bundles. The design consists of an outer copper corrosion barrier vessel and an inner steel load-bearing vessel. The used fuel bundles are first placed within a fuel basket which is then loaded into the inner vessel. Each basket consists of an assembly of carbon steel tubings in a closed packed arrangement. The outer copper corrosion barrier is designed to collapse onto the inner steel container under repository pressure loadings and, thereafter, be supported by it. The container will be encased in bentonite clay for emplacement in disposal rooms or in boreholes. The Canadian design concept is similar in several respects to the Swedish and Finnish designs and was developed considering the present siting uncertainties for a repository.

Used fuel must be shipped to the central extended storage or disposal site in containers that shield, contain the radioactivity and dissipate the heat. The containers may be transported via road, rail and/or water. Many of the requirements for used fuel storage containers also apply to used fuel transportation containers; additional requirements also arise from a consideration of the extreme weather conditions that can be experienced in Canada. The containers must be appropriately packaged for transportation; the packaging consists of impact limiters, impact armouring and associated attachments. Packages for transporting spent fuel constitute a Type B package. Such packages are required to withstand expected accident conditions without breach of containment or an increase in radiation level that potentially could endanger the general public and those involved in rescue or clean-up operations.

Two designs exist for transporting Canadian used fuel, namely, OPG's transportable DSC and OPG's Irradiated Fuel Transportation Container (IFTC). These represent two relatively different design concepts. The IFTC, similar to the DSC, is rectangular; however, it is of stainless steel construction. It can accommodate half of the DSC's payload, i.e., two fuel modules weighing 5 Mg. While the DSC has a welded lid, is intended for single use and has a design life of 50 years, the IFTC has a bolted closure, is intended for repeat use and has a design life of 20 years. One main disadvantage of the DSC is its relatively large weight; despite this, transportation by road is considered to be feasible. The IFTC design can also accommodate non-OPG fuel storage baskets.

In contrast to the IFTC, transportation containers for enriched LWR fuel have a multi-shell cylindrical structure (lead is sandwiched between inner and outer steel shells) which also incorporates neutron shielding. Similar to the IFTC, containers for Gas Cooled Reactor fuel are also rectangular in cross-section because the fuel element has a short length. Unlike the LWR fuel transportation containers, the IFTC requires no fins for heat dissipation because CANDU fuel is much cooler; the absence of fins facilitates decontamination and makes the container cheaper to manufacture.

1.0   INTRODUCTION AND BACKGROUND

1.1   Commercial Nuclear Power Generation in Canada

There are twenty-two CANDU commercial power reactors in Canada, twenty of which are located in Ontario and one each is located in Quebec and in New Brunswick. The reactors in Ontario, which are owned by Ontario Power Generation (OPG), are located on three sites, namely, Pickering, Bruce and Darlington. The reactor in Quebec, which is located at Gentilly-2, is owned by Hydro Quebec and, that in New Brunswick, located at Point Lepreau, is owned by New Brunswick Power. The electricity generating capacity for all the reactors is approximately 15, 000 megawatts. In addition to the commercial power reactors, there are also 3 partially decommissioned demonstration reactors and a number of research and isotope production reactors.

The operation of nuclear reactors results in the generation of radioactive waste. In Canada, three principal types of waste are generated: High Level Waste (HLW) consisting exclusively of used fuel, Intermediate Level Waste (ILW) consisting principally of high activity resin waste and irradiated core components and Low Level Waste (LLW) consisting of assorted materials such as rags, protective clothing, used equipment and liquids.

Aside from most of the original uranium oxide[1], used fuel contains significant levels of fission products and actinides. It is, therefore, characterized by high radiation fields and significant heat generation rates. Hence, the used fuel must be stored in water-filled pools to shield against its radiation and to dissipate its decay heat. In contrast, ILW is characterized by relatively moderate radiation fields and low heat generation rates. This waste typically contains fission and activated corrosion products but relatively minor levels of actinides. Handling and storage of this waste, therefore, requires use of shielding also, but heat dissipation is not an issue. Compared to ILW, LLW contains much lower levels of radioactivity, particularly of long-lived radionuclides such as carbon-14. Except possibly during handling, shielding is not required for storage of LLW.

The estimated inventory of used fuel from Canadian commercial power reactors to the end of 1998 was approximately 5400 m^3 corresponding to approximately 1,350,000 fuel bundles[2] [1]. In comparison, the inventory from demonstration and research reactors was approximately 194 m^3 corresponding to approximately 5,600 fuel bundles.

Figure 1 is an illustration of a typical CANDU fuel bundle.

While used fuel, after discharge from the reactor, is initially stored under water, it may, after a minimum cooling duration, be transferred into dry storage containers. Dry storage is being increasingly practiced at several sites in Canada because pool storage capacity is becoming full. Both wet and dry storage of used fuel, nevertheless, represent an interim measure for managing the waste. Eventually, more permanent methods must be implemented.

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[1] Discharged CANDU fuel still contains about 98% of the original uranium; the rest is converted into fission products.

[2] CANDU fuel is contained within zirconium alloy cladding tubes or elements in the form of uranium dioxide pellets. An assembly of fuel elements is called a fuel bundle. For example, the Darlington fuel bundle contains 37 elements.
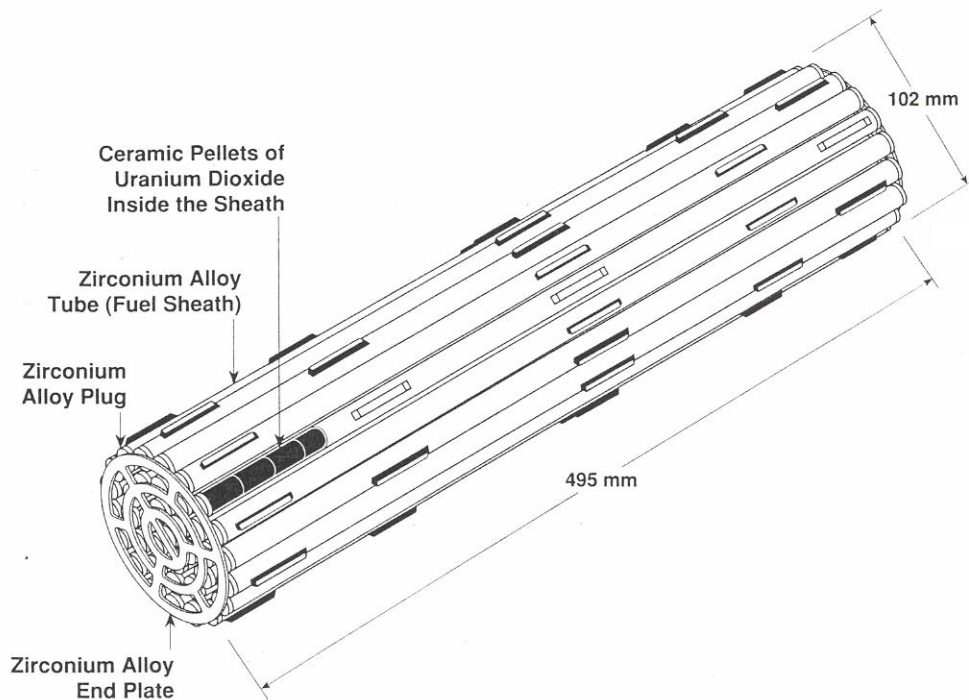
Figure 1   Typical CANDU Fuel Bundle

1.2   Nuclear Waste Management Organization, Its Mandate and Options for the Long Term Management of Used Fuel

The Nuclear Waste Management Organization (NWMO) was established under the Nuclear Fuel Waste Act (NFWA) which came into force in November 2002. Under this Act, the NWMO is mandated to examine a range of approaches for the long-term management of used fuel. The Act also requires the establishment of an Advisory Council to review the work performed by the NWMO. Within three years of the legislation coming into force, the NWMO is required to submit, to the Minister of Natural Resources, proposed approaches for the management of used nuclear fuel, along with views of the Advisory Council and a recommended approach. The NWMO will then implement the long-term approach selected by the government.

The NFWA is the most recent milestone in a 25-year program to identify and implement a long-term management approach for used nuclear fuel in Canada. The legislation represents, in part, the Government of Canada's response to the findings of the Seaborn Panel on Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment. This Panel assessed the deep geological disposal approach proposed by Atomic Energy of Canada Limited (AECL) and reported in March 1998 that although the deep geological disposal concept had been adequately demonstrated technically, it's broad public acceptance had not been demonstrated.

While deep geologic disposal in the Canadian Shield has been identified as one of the options for further consideration in the NFWA, the NWMO is also required to examine a range of other approaches for the management of used fuel. The other principal approaches to be examined are 1) extended storage at reactor sites and 2) extended storage at a central site. The duration of extended storage has not been specified but is likely to be significantly longer than the

duration (several decades) associated with the interim storage of used fuel or alternately the life of a nuclear station.

The NWMO's review of different management options involves diverse issues ranging from the identification of societal, ethical and community implications to specific issues concerning the safety and security of used fuel storage and transportation. To clarify these specific issues, the NWMO has commissioned the preparation of a series of background papers. This paper addresses the status of storage, disposal and transportation containers for managing used nuclear fuel.

1.3   General Containment Concepts and Design Considerations for the Long Term Management of Used Fuel

Used fuel is highly radioactive and contains chemically toxic elements. Protection of humans and other organisms from its harmful effects requires that the hazard is contained and isolated from the natural environment, that radiation be reduced to acceptable levels and that radioactive decay heat be removed by cooling.

The objectives of containment and shielding typically require the provision of multiple barriers. For example, during wet storage inside a used fuel storage pool, the zirconium alloy cladding serves as the primary containment barrier. Water helps to maintain the integrity of this barrier by effectively dissipating the thermal stresses in the fuel arising from decay heat generation. The cladding, the water, the concrete structure of the fuel pool, the exclusion zone around the facility and the monitoring of radioactive releases constitute the multiple barriers that prevent the release of radioactive material to the environment. The depth of water in the fuel pool provides the degree of shielding required protecting workers.

Because used fuel poses a long-lived hazard, containment of the waste and shielding from its radiation are key requirements for its long-term management. For this purpose, the fuel will either remain at the reactor site in dry storage facilities (existing fuel pools would eventually be decommissioned) or be transported to a disposal or a centralised storage site. The appropriate degree of containment during shipment is achieved by requiring the lids on the transportation containers to be welded shut or securely bolted. The heavy-walled containers provide the requisite degree of shielding. Because the payload being transported would have cooled for several years prior to shipment, passive heat dissipation is adequate to maintain fuel integrity.

Considerations for fuel containment, shielding and cooling at a long-term storage or disposal site are similar to those for interim storage facilities and would also need to address fuel handling, repackaging and transfer activities. The emplacement of waste containers in these facilities would necessitate procedures for minimising radiation exposure to workers. Design of disposal containers and the multiple barriers to be placed between them and the boundary of the repository must ensure that any future migration of radionuclides from the repository via groundwater seepage, container corrosion and dissolution of the waste would not result in unacceptable impacts to humans and the natural environment.

1.4   Scope of Background Paper

The purpose of this paper is to present readers with a factual description of the current status of storage, disposal and transportation containers for the long-term management of used fuel.

Section 2 presents the current status of used nuclear fuel storage. Sections 3, 4 and 5 address containers for extended storage, disposal and transportation, respectively. These sections are aligned with the principal mandate of NWMO to assess long-term storage and disposal options. Section 3 is based on reference storage technologies being practiced today; typically, the design lives of existing storage containers do not exceed 50 years. It is, therefore, anticipated that the stored fuel would be periodically re-packaged during its extended storage. Because some dry storage systems also have a dual role as transportation containers, a degree of overlap between Sections 3 and 5 was unavoidable. Conclusions are presented in Section 6.

It should be noted that containers for used fuel are frequently referred to in the literature as 'casks' (especially transportation containers) and occasionally as 'canisters'. In this paper, the more general terminology, namely, 'container' is used in preference to these terms.

2.0 CURRENT STATUS OF USED NUCLEAR FUEL STORAGE

The world-wide status of used fuel interim storage is discussed in this Section. The objectives for interim storage are:

- To manage the used fuel in a safe (i.e. ensure adequate shielding from radiation and protection of environment by minimising radionuclide releases), reliable and economic manner,

- To maintain the integrity of the used fuel by effectively dissipating the decay heat; this will ensure that the fuel is retrievable in the future, and

- To maintain used fuel under sub-critical conditions, i.e., under conditions where spontaneous nuclear chain reactions cannot occur (this is particularly important for Light Water Reactor (LWR) fuel but not for CANDU fuel).

2.1 Status of Wet Storage of Used Fuel

Wet storage technology involves the storage of used fuel in water-filled pools. The pools are lined with epoxy or stainless steel to prevent leakage of water. They have double concrete walls so that any leakage through the inner wall can be collected and directed to a cleanup system. The water provides shielding against the radiation emitted by the stored fuel and also removes the decay heat. It is cooled by circulation through heat exchangers and purified by filtration and ion exchange. Based on current experience, water pools can provide safe storage of used fuel for periods of at least 50 years.

In addition to the storage pool, a wet storage facility may have one or more of the following facilities:

- Reception area for dry storage/transportation containers,

- Facilities for decontaminating containers, transfer of used fuel into containers, maintenance and dispatch,

- Auxiliary services including radiation monitoring, water-cooling and purification, solid radioactive waste handling, ventilation and power supply.

Used fuel pools are located either at the reactor site or away from the reactors.

At-Reactor Pools

At-Reactor pools receive the discharged fuel directly from the reactor. They are the most common types of used fuel storage. The pools are located either within the reactor building or in an adjacent building connected to the reactor. Most At-Reactor pools were built as part of the original reactor construction. Shortage in storage capacity has led to improved designs for racks used to store fuel in the pools.

The capacity of At-Reactor pools varies between countries and depends on the fuel management strategy at the time the reactors were built. As a result of decisions to defer reprocessing or disposal, some countries built sufficient pool capacity to store a significant

portion of the expected lifetime used fuel arisings. On the other hand, other countries developed only modest capacity anticipating short-term onsite storage needs before the transportation of fuel off-site.

The At-Reactor pool storage capacity world-wide [2] is summarized in Table 1. Note that all used fuel in Canada is stored at the individual reactor sites where it is generated.

Table 1   World-Wide At-Reactor Wet Storage Capacity*

Country	Number of Pools	Capacity Mg HM [a]
Canada	10	31,407
France	54	11,290
Germany	27	5,087
Japan	45	15,050
Korea, Rep.	12	5,875
Russia	24	5,240
Spain	9	3,820
Ukraine	16	3,010
UK	35	2,666
USA	118	60,700
Other countries	55	12,111
Total	**405**	**156,356**

*   Data are for 1998.
a   MgHM denotes Megagrams or tonnes Heavy Metal.

Away-From-Reactor Pools

Used fuel is received in a transportation container at the Away-From-Reactor pool facility. Both wet and dry unloading is employed. Dry unloading is performed in a hot-cell[3] type facility.

Away-From-Reactor pools may be further divided into two categories:

1   Storage at the Reactor Site but largely independent of the reactor: These pools can continue to operate even after the reactor has been finally shutdown. Many such facilities are located at older power plants because their original At-Reactor pools were not sized for lifetime fuel waste arisings.

2   Off Site storage at an independent location: Most of this type of storage is in the form of pools at reprocessing plants, particularly in France, UK, Russia and Japan.

The World-wide Away-From-Reactor pool storage capacity is summarised in Table 2 [2]. Comparison with Table 1 indicates that Away-From-Reactor facilities are far fewer in number

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[3] A hot-cell is a shielded facility with features such as lead glass windows and remote manipulators and/or robotics.

than At-Reactor facilities and Away-From-Reactor capacity is about one-third that of At-Reactor capacity. Canada does not have Away-From-Reactor wet storage facilities.

Table 2   World-wide Away-From-Reactor Wet Storage Capacity*

Country[a]	Number of Pools	Capacity, Mg HM[b]
Finland	2	1,450
France	4	14,500
Japan	3	4,300
Russia	6	12,960
Sweden	1	5,000
Ukraine	1	2,000
UK	4	10,350
Other [c]	7	4,767
Total	**28**	**55,227**

* Data are for 1998.
a Facilities in France, Japan, Sweden and USA are off site; elsewhere, the facilities are at the reactor site.
b Mg HM denotes Megagrams or tonnes Heavy Metal.
c Argentina, Belgium, Bulgaria, Germany, India, Slovakia and USA have one facility each.

2.2   Status of Dry Storage of Used Fuel

Dry storage has been added at various power plants to increase storage capacity. After used fuel has cooled for a number of years in wet storage, the rate of heat generation decreases sufficiently, as a result of radioactive decay, to allow the fuel to be transferred into dry storage facilities. The storage of zirconium-alloy-clad used LWR fuel in an inert atmosphere[4], at internal temperatures of up to 450°C, is a proven technology [3,4]. Lower burnup[5], cooler CANDU fuel can be stored dry in air at temperatures up to 160°C [5].

Compared with wet storage, dry storage has the following advantages:

- Reduced production of radioactive waste such as filters,

- Electrical, water and maintenance inputs are required only for monitoring and surveillance leading to a lower operating cost,

- Less contamination of the storage facility,

- Little or no corrosion of fuel sheaths,

- Less radiation exposure to operating personnel, and

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[4] Storage of fuel in an inert atmosphere improves heat transfer and prevents fuel oxidation.

[5] Burnup refers to fuel utilization. It can be expressed as a percentage of the fuel used before it must be replaced. It is more usually expressed on an equivalent energy basis.

- Modular and easy construction means required capacity can be added in stages.

The dry storage systems, which are mostly of the Away-From-Reactor category, were initially single purpose systems and provided storage only. With technology development, dual-purpose systems became available which allowed both storage and transportation without the need to re-handle fuel assemblies.

Since the world's first dry storage facility was constructed in 1970 to store Magnox fuel[6] in the UK (prior to reprocessing), the numbers and types of dry storage facilities globally have increased significantly. Dry storage facilities are being increasingly commissioned in several countries including Canada. Table 3 presents an overview of the dry storage capacity world-wide [6]. The countries with major dry storage capacities are Canada, Germany and the USA. The total installed global capacity is distributed according to the type of storage facility as follows: vaults, 15%; containers, 60% and silos, 25% (a description of these facilities is given in Section 3.4.1).

Table 3   World-wide Dry Storage Capacity*

Country	Capacity (Mg HM[a])
Argentina	1,000
Belgium	800
Canada	13,311
Czech Republic	600
France	180
Germany	8,353
Hungary	162
Korea	1,421
UK	958
USA	6,859
Other Countries[b]	174
Total	33,818

*   Based on 1999 data [IAEA].
a   Mg HM denotes Megagrams or tonnes Heavy Metal.
b   India, Japan and Armenia.

Table 4 compares the world-wide installed capacities for dry and wet used fuel storage [2]. Note that the total dry storage capacity given in Table 4 differs significantly from the corresponding estimate in Table 3 possibly because of inconsistent accounting in the two data sources. Based on the higher estimate in Table 4, dry storage represented approximately 17% of the installed fuel storage capacity in 1998.

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[6] Magnox fuel is natural uranium, gas cooled reactor, fuel contained in magnesium alloy cladding.

Table 4   Storage Capacity for Used Fuel World-wide*

Type of Storage	Number of Facilities	Capacity (Mg HM[a])
At-Reactor Pools	405	156,356
Away-from-Reactor Pools	28	55,227
Dry Storage	39	43,138
Total	472	254,721

*   Based on 1998 data.
a   Mg HM denotes Megagrams or tonnes Heavy Metal.

3.0   CONTAINERS FOR EXTENDED STORAGE OF USED FUEL

3.1   Concept of Extended Storage

As described in Section 2, used nuclear fuel from commercial power plants is stored both in used fuel pools and increasingly in dry storage containers. In Canada, the used fuel is stored in two forms: at OPG sites, it is stored in a rack system called a module[7] while at non-OPG sites, the fuel is stored in sealed containers called baskets[8]. At OPG sites, the fuel modules are first placed in wet storage and subsequently transferred into transportable Dry Storage Container (DSC)s (each container houses 4 modules; see description in Section 3.4.3). Similarly, at non-OPG sites, the fuel baskets after initial cooling in water-filled pools are transferred into dry storage vaults and silos (see Section 3.4).

Following final reactor shutdown, all the stored fuel will need to be transferred into extended dry storage facilities until a more permanent management method is established. Current concrete storage systems typically have a design life of 50 years. Their actual life may, however, be much longer [7]. Conditions such as low humidity, constant temperature, absence of chemical pollutants and avoidance of exposure to freeze-thaw cycles would enhance their life expectancy. Metallic containers are expected to have longer lifetimes than concrete containers.

The concept of extended storage is one of storage in perpetuity. Even if improved engineering leads to a reduced rate of degradation in performance of storage systems, their life may still not exceed a few hundred years. To facilitate storage of used fuel over an extended period, it will, therefore, be necessary to transfer the fuel, at the end of the service life of existing storage facilities, into new storage structures.

Because of the finite life span of buildings and storage and containment structures, there must, therefore, be a rolling program of demolition and renewal to maintain facility operations indefinitely [8]. Also, deterioration in the condition of fuel baskets and modules may necessitate their replacement when storage systems reach the end of their service life.

3.1.1   Extended Storage at a Centralized Site

Compared to extended storage at individual reactor sites, the construction and operation of a centralized extended storage facility (CESF) would benefit from the economies of scale although this would be offset by the need to transport used fuel from the individual sites. For a Canadian CESF, the fuel arriving at the facility would be in three forms:

- In presently used DSCs from OPG sites,

- In the Irradiated Fuel Transportation Container or IFTC (according to the existing design, each container houses 2 modules; see description in Section 5.4.3) - the IFTC would be used to transport used OPG fuel that is not contained within DSCs at the time of transportation; and

- In transportation containers for non-OPG fuel baskets (a design does not exist currently).

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[7] Ninety-six bundles are stored in horizontal tubes held in a rectangular framework.

[8] At Gentilly-2 and Point Lepreau, sixty bundles are stored vertically in a basket, which is then sealed.

These containers would be received at the CESF facility over a period of possibly 30 years at which time the facility would enter a dormant phase.

Concepts for a CESF may include the following [8]:

- Casks and Vaults in Storage Buildings (CVSB).

- Surface Modular Vault (SMV).

- Casks and Vaults in Shallow Trenches (CVST).

- Casks in Rock Caverns (CRC).

The reader is referred to Section 3.4.1 for a description of containers and vaults. CVSB and SMV are above-ground facilities. CVST are located partially underground but above the water table and are mounded over, while the CRC is located 50 m below ground level, either above or below the water table. The earthen cover of the CVST provides intrusion resistance and minimises precipitation infiltration. The CRC concept involves storage in underground caverns excavated from bedrock.

The CVSB, CVST and CRC concepts minimise repackaging of fuel at the CESF because they accept fuel in the form of existing DSCs, fuel modules and fuel baskets. On the other hand, the SMV facility accepts fuel only in the form of fuel modules and fuel baskets; hence fuel stored at OPG reactor sites in transportable DSCs would have to be unloaded and instead transported to the CESF using the IFTC.

In the cases of CVSB and CVST, the received DSCs will be directly emplaced, received OPG fuel modules would be packaged and stored within DSCs and received non-OPG fuel baskets would be packaged inside containers and then stored in vertical tube arrays within a series of engineered concrete vaults. The SMV concept involves the storage of fuel bundles, sealed in either baskets or module canisters, inside concrete vaults. The CRC concept involves the direct emplacement of received DSCs and also the transfer of received fuel bundles, in the form of modules or baskets, into self-shielded storage containers for emplacement in the caverns.

3.1.2 Extended Storage at Reactor Sites

Consider for the purpose of discussion, an extended storage facility at an OPG reactor site. Used fuel received at this Reactor Extended Storage Facility (RESF) would be in the form of DSCs and fuel modules.

Concepts for a RESF include the following [9]:

- Casks in Storage Buildings (CSB).

- Surface Modular Vault (SMV).

- Casks in Shallow Trenches (CST).

The CSB and CST concepts are analogous to the CVSB and CVST concepts (vault storage is not required in the absence of fuel baskets). The CSB option is a continuation of the current dry

storage methodology. Its implementation will not require any major design changes but will require a review of the monitoring and inspection programme.

Implementation of the SMV alternative will require that all fuel modules, previously packaged into DSCs, be retrieved and sealed into module canisters before storage in tubes within the SMV vault buildings. Existing DSCs and associated facilities would then be decommissioned.

In the CST alternative, after all the used fuel has been packaged into DSCs and emplaced in trenches, the existing DSC buildings would be decommissioned.

3.2   General Considerations for an Extended Storage Facility

The design of an extended storage facility will depend on whether it is a central or a reactor site facility and also on the specific concept selected for that facility. Design of the handling and processing facilities at the site would need to consider the specific forms in which fuel is received at the site. Based on a 30 year period for fuel receipts, the CESF would need to be sized to receive, handle and package used fuel bundles at the rate of approximately120,000 bundles per year [8]. In contrast, a RESF would need to be sized for the specific throughput at an individual site.

In general, an extended storage facility would be designed to have the following functions:

- Receipt, re-packaging and emplacement of fuel: Facilities are required to offload the fuel, re-package it in hot cells if required and emplace the waste in the storage structures.

- Provide safe containment: The containment barriers depend on the type of storage system. DSCs provide a single welded containment barrier. On the other hand, double containment is achieved when sealed fuel baskets are placed within tube arrays in a vault and then the tubes are sealed.

- Monitoring and inspection: This includes periodic radiation surveys, condition monitoring of the storage containers and vaults, and periodic monitoring of the performance of drainage and ventilation/cooling systems.

- Safe retrieval of the used fuel: The facility would be designed to permit retrieval of used fuel from storage systems if their performance falls below specifications and then to transfer the fuel into new storage systems.

- Provide cooling: This is required to prevent excessive fuel and storage system temperatures. Passive air-cooling is generally adequate to remove decay heat. In concepts such as the CRC, forced air-cooling is, however, required because of a greater resistance to movement of air.

- Ensure adequate shielding: Adequate shielding is required during all phases of fuel handling and storage.

3.3 Overall Requirements for Storage Containers

In general, containers must provide safe containment of the used fuel from the time of loading through handling, transportation, emplacement and during storage. Key performance and design requirements for the container are [3-5, 7]:

- Storage containers should have an extended design life to minimise the frequency of re-packaging the used fuel.

- The design should give due consideration to corrosion protection of metallic surfaces, ease of decontamination and protection of the external surfaces during emplacement.

- Container cavities should be preferably filled with helium gas (under slight pressure) to protect the fuel bundles from potential oxidation and to facilitate leak testing[9] of the container.

- Heat transfer characteristics of the container must ensure that the fuel sheath and the container's external surface temperatures do not exceed their maximum stipulated limits.

- Containers should provide adequate shielding against radiation.

- Containers should be designed to withstand natural hazards such as earthquakes, floods and tornadoes as well as hazards arising from human activities such as fires, explosions and plane crashes.

- Containers must retain their structural integrity over the design life. Structural strength requirements for stacking must be met (for instance, the SMV storage concept requires containers to be stacked two high).

- Containers should be designed for ease of inspection.

3.4 Extended Storage Container Designs

3.4.1 Design Concepts for Used Fuel Storage Containers

Globally, three main types of dry storage systems are currently in use [2, 6]:

1. Concrete vaults, which are large ventilated buildings and hold 600-2000 Mg,

2. Concrete containers and silos, which hold 5-15 Mg, and

3. Metal containers, which hold 10-17 Mg.

Concrete Vaults

Vaults are above or below ground reinforced concrete buildings containing arrays of storage cavities (see Section 3.4.3). Shielding is provided by the exterior concrete structure. Used fuel, received at a vault facility is removed from the transportation containers and if required is sealed

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[9] Escape of helium can be monitored to determine if a leak is present.

within a metal canister. The canister may be backfilled with an inert gas and then housed in a storage cavity in the vault.

Heat is removed either by forced or natural air convection; temperature differences of about 15°C between incoming and outgoing air are typical. The heat removal capacity of vaults is considerably larger than that of containers. Vaults can maintain cladding temperatures of 5 year cooled Pressurised Water Reactor (PWR) assemblies below 200°C; on the other hand, the lower heat removal capacities of concrete and metal containers result in PWR fuel temperatures of approximately 350°C. Vaults can maintain cladding temperatures of 7 year cooled CANDU fuel elements below 150°C [4].

Concrete Containers

Concrete containers are used to store and transport used fuel (see also Section 3.4.3). Reinforced, regular or high-density concrete is used for structural strength and radiological shielding. Containers designed for LWR fuel use borated concrete (the boron provides neutron shielding); this type of concrete is not required for storing used CANDU fuel assemblies because of the much lower neutron flux. In some concrete systems, sealed metal canisters, containing the used fuel, are housed and cooled by natural convection while in other systems, the fuel is housed inside a metal liner within the container cavity (e.g. the DSC) and cooled by conduction through the structure. Concrete containers that rely on conductive heat transfer have more thermal limitations than those relying on natural air convection. Typically, surface temperatures of the container are only a few degrees centigrade above ambient.

Concrete Silos

Silos are modular concrete reinforced structures (see Section 3.4.3) which may be stored indoors or outdoors. They are usually circular in cross-section. The fuel may be stored vertically or horizontally. The concrete provides shielding while containment is provided either by a separate sealed metal container or by an integral inner metal liner, which can be sealed after loading of fuel. Fuel is loaded into silos at the storage site.

Metal Containers

Metal containers are used to store, transport and eventually dispose of used fuel (see Section 5.4.4). The structural materials for these containers may be forged steel, nodular cast iron or a steel/lead sandwich (see also Section 5.4.2). The container walls provide shielding against radiation. The containers are fitted with an internal basket that provides structural strength and assures sub-criticality for LWR fuel (criticality is not an issue for CANDU fuel). Metal containers may have a finned outer surface to facilitate cooling by convection in addition to cooling by radiation; typically, container surface temperatures are 10 to 20°C above ambient. The containers usually have a double lidded closure system, which may be bolted or welded and can be monitored for leak tightness.

3.4.2   Choice of Container Materials

A brief discussion of metals used for fabrication of containers is presented in Section 5.4.2. Only concrete is discussed here.

Concrete is overwhelmingly the choice for shielding material in a large number of storage container designs. It is a strong and inexpensive material, which is adaptable to both block and monolithic[10] types of construction [10]. Ordinary concrete of density 2.3 Mg/m^3 generally contains 7-8 weight % water. The presence of elements with moderately high mass numbers, such as calcium and silicon, at a concentration of approximately 50 weight %, gives concrete a good attenuation property for gamma rays; the presence of water in the concrete imparts it with the ability to shield against neutrons. Various special high density concretes such as barytes concrete (this contains 60 weight % barytes, which is mainly barium sulfate, and has a density of 3.5 Mg/m^3) and iron concrete (this concrete contains 57 weight % steel punchings and has a density of 4.5 Mg/m^3) incorporate elements of fairly high mass numbers. These heavier concretes attenuate both gamma rays and neutrons to a greater extent than ordinary concretes.

The concrete used in OPG's DSC has a minimum density of 3.5 Mg/m^3 [5].

3.4.3   Canadian Designs

Design features of dry storage facilities at currently operating Canadian reactor sites are briefly described here. In contrast to the dual purpose storage/transportation DSCs used at OPG stations, the facilities at Hydro Quebec and Point Lepreau can only be used for storage.

Vaults at Gentilly-2

Concrete vaults, called CANSTOR (an application of AECL's MACSTOR concept as described in Section 3.4.4) are used for storing used fuel at Gentilly-2. The vaults are located outdoors on a concrete foundation slab and are passively cooled. A cross-section of the vault [11] is shown in Figure 2. The vault dimensions are: 8.1 m height, 7.5 m width and 21.6 m length [6]. Each vault has 20 carbon steel liners; each liner stores 10 stainless steel baskets.

Used fuel, after a minimum cooling period of 7 years in the fuel bay, is loaded into the stainless steel baskets, 60 bundles to a basket [6]. The loaded basket is covered and raised into a shielded workstation where the basket and associated fuel are air-dried. A cover is then seal-welded to the basket. The sealed baskets are transported to the concrete vaults using a shielded flask. After the baskets are loaded into a liner, a shield plug is inserted and welded to the liner. During storage, the space between the liner and the baskets is monitored and sampled via penetrations. Provision of IAEA safeguard seals[11] prevent removal of the shield plugs without the seals being broken.

Silos at Point Lepreau

Cylindrical reinforced concrete silos are used to store used fuel at Point Lepreau. The silos are located outdoors on a concrete foundation slab and are passively cooled. A cross-section of the silo [12] is shown in Figure 3. The silo dimensions are: height 6.52 m and external diameter 3.07 m [6]. They have an internal epoxy coated carbon steel liner of internal diameter 1.12 m. Nine baskets are stored in each liner or silo.

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[10] A monolithic concrete structure has no joints between its various faces; it is produced by a continuous pour of the concrete paste into a mould and then allowing the paste to cure.
[11] The seals guard against diversion of fissile material.

AIR OUTLET

Removable Shield Plug

Carbon Steel Liner

Storage Cavity
(Stores Fuel Baskets 10 High)

AIR INLET

Concrete
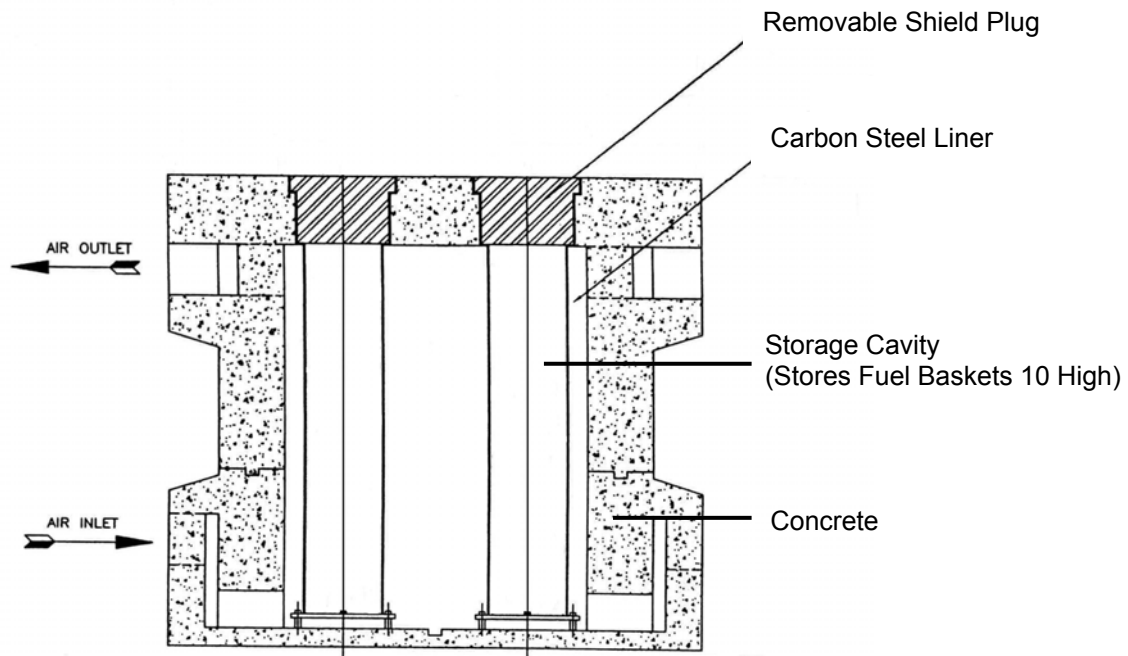
Figure 2   A Typical Cross-Section of the Vaults at Gentilly-2

Removable
Shield Plug

Carbon Steel Liner

Storage Cavity
(Stores Fuel
baskets 9 High)

Concrete
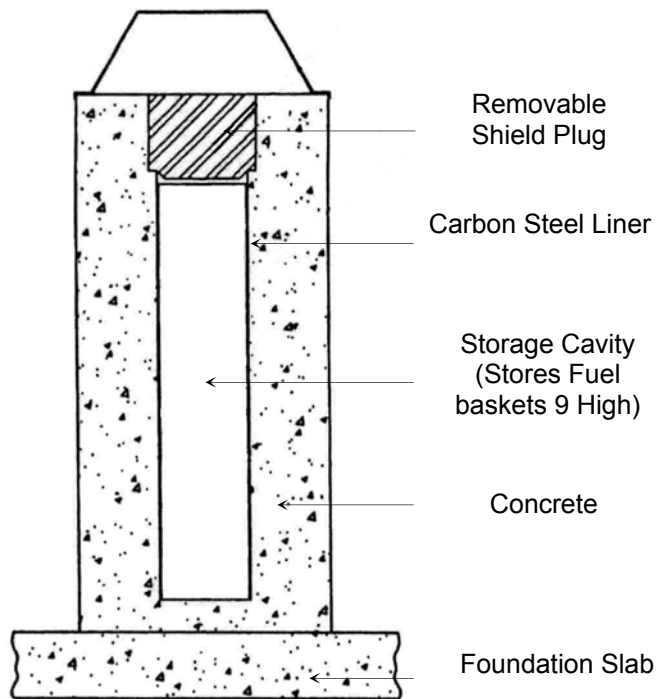
Foundation Slab

Figure 3   A Typical Cross-Section of the Silos at Point Lepreau

Procedures similar to those employed at Gentilly-2 are used to transport and load fuel baskets. A shield plug is welded to the liner after loading is completed. Provision of IAEA safeguard seals prevent removal of the shield plug without the seals being broken.

Concrete Containers at OPG Reactor Sites

Concrete containers (DSCs) are used at OPG sites for dry storage of used fuel. As illustrated in Figure 4, the DSC is a free standing reinforced concrete rectangular container with an inner steel liner and an outer steel shell [5,13]. It is made of two sub-assemblies, a lid and a base. The Pickering DSC has a capacity for four fuel modules or 384 used fuel bundles. Fuel is cooled for a minimum of 10 years in pools before being loaded into a DSC.

The overall dimensions of the container are 2.120 m x 2.419 m by 3.550 m in height. The space between the inner liner and outer shell is filled with 0.52 m of reinforced high density concrete. This provides radiation shielding while adequately dissipating decay heat. The DSC weighs approximately 60 Mg when empty and 70 Mg when fully loaded. With impact limiters placed on each end of the DSC (for off-site transportation), the transportation package weighs 101 Mg.

Other key features of the DSC are listed below:

- A weld between the base plate of the container lid and the perimeter flange of the container body secures the storage lid in place. The vent and drain housings have steel shielding plugs that are seal welded.

- Helium is used as the inert cover gas in the DSC cavity to protect the fuel bundles from oxidation reactions and to facilitate leak testing of the containment boundary.

- The DSC outer shell is coated with epoxy/polyurethane paint. This facilitates its decontamination following wet-loading operations.

- Lift plates on the outer shell of the DSC are designed for use with a dedicated lifting beam or a transporter.

- Two separate, U-Shaped, 25.4 mm outer diameter stainless steel tubes are embedded in the DSC walls, lid and floor. The tubes are used for attachment of IAEA Safeguards seals.

3.4.4 Other Designs

A number of vendors offer dry storage and transportation systems for non-CANDU used fuel. Some storage system designs are discussed here; designs for dual-purpose storage / transportation systems are discussed in Section 5.4.4.

Key features of some storage systems [14] are presented in Table 5. Three of the systems shown, namely, the NUHOMS, MACSTOR and MVDS are vault type systems, which are based on the storage of used fuel inside metal containers that are then placed within concrete structures. In contrast, the VSC system is a shielded container system. The NUHOMS system is extensively used in the US. Compared to the horizontal storage of fuel in the NUHOMS system, the MACSTOR and MVDS systems store fuel in a vertical configuration.
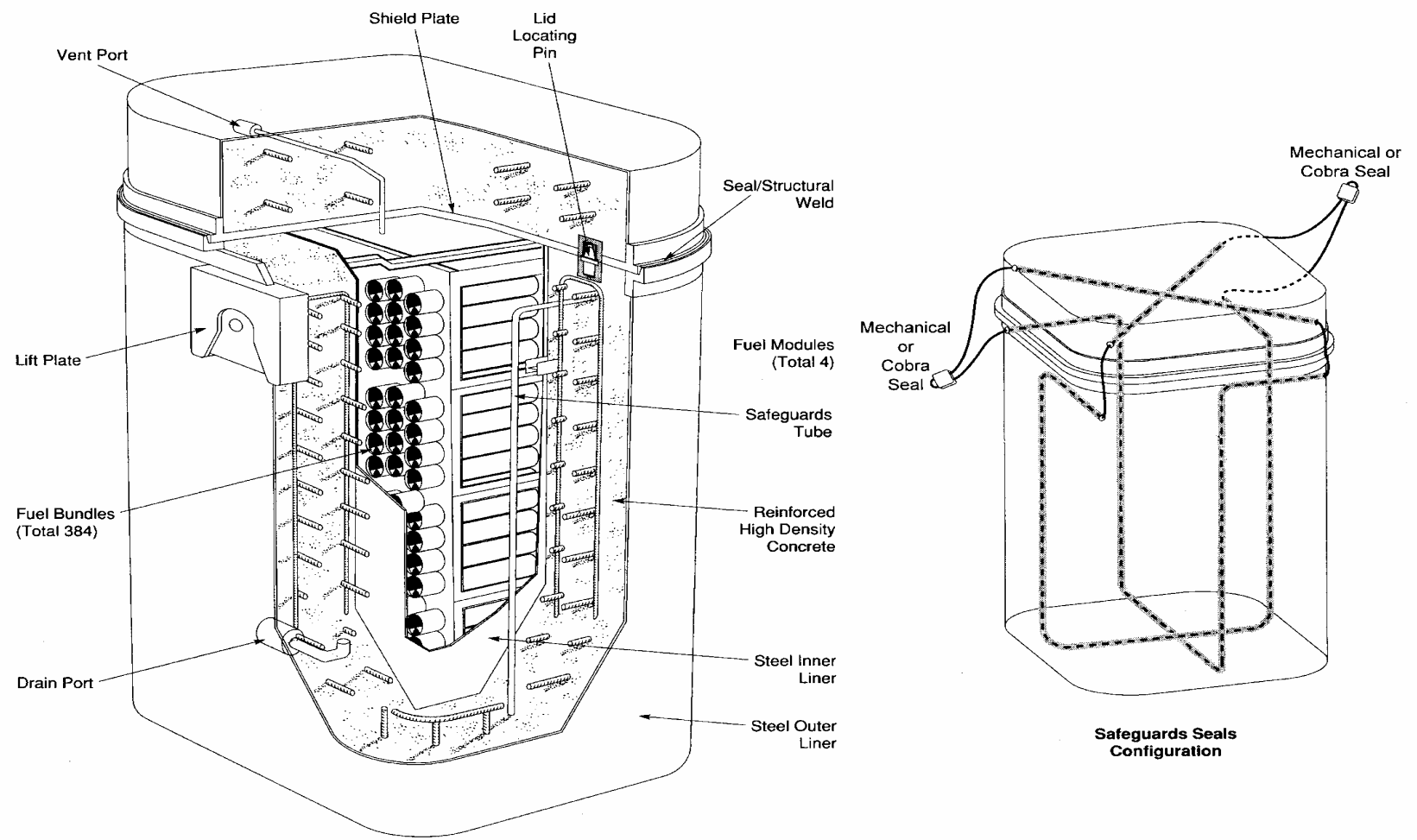
Figure 4   Ontario Power Generation's Used Fuel Dry Storage Container

Table 5   Examples of Available Dry Storage Technologies

System	Key Features
NUHOMS Offered by Vectra Technologies, Inc. , USA	• Utilises a ventilated reinforced concrete horizontal storage module to store LWR fuel assemblies, which are sealed inside a stainless steel canister. • Canister is transferred in a cask and loaded horizontally in module. • Diameter of canister shell assembly is 1708 mm. • Overall length of canister is 4724 mm for PWR fuel and 4978 mm for BWR fuel. • Canister holds 24 PWR or 52 BWR assemblies.
Ventilated Storage Cask (VSC) Offered by Sierra Nuclear Corporation, USA	• Utilizes a ventilated concrete storage container and a steel basket. • Baskets are vertically loaded. • Basket diameter is 1588 mm and about 4318 mm length. • Concrete container has a diameter of 3353 mm and height of 5004-6096 mm. • Basket holds 24 PWR assemblies or 65 BWR assemblies.
Modular Air Cooled Canister Storage (MACSTOR) Offered by AECL, Canada and Transnuclear, Inc., USA	• Utilizes a rectangular reinforced concrete vault to vertically store 16 carbon steel canisters holding LWR fuel (other types of fuel can also be stored). • The vaults at Gentilly-2 represents an application of MACSTOR technology for CANDU fuel called CANSTOR. • Vault has a height of 6.6 m, width of 9 m and length of 22 m. • Canisters hold 21 PWR or 44 BWR assemblies.
Modular Vault Dry Store (MVDS) Offered by GEC Alsthom, UK	• Fuel assemblies in baskets are stored inside vertical carbon steel containers within a vault structure. • Can store different types of fuel. • Vault for LWR fuel can typically store 220 PWR or 400 BWR fuel assemblies.

In general, the LWR systems require the fuel to be cooled for 5-10 years before storage. Typically, the fuel is stored within an inert nitrogen or helium gas environment.

In contrast to OPG's DSC, the systems in Table 5 have a cylindrical configuration. Such a configuration is not optimal for CANDU fuel because the fuel bundles have a much shorter length [15].

4.0 CONTAINERS FOR DISPOSAL OF USED FUEL IN DEEP GEOLOGICAL REPOSITORY

4.1 Concept of Disposal of Used Fuel in a Deep Geological Repository

Containers for the disposal of used fuel are typically designed for a very long life. When the containers eventually fail by corrosion as a result of ground water ingress into the repository, waste constituents can migrate out of the disposal facility and enter the biosphere. Factors which affect container corrosion are [15,16]:

- Oxidation/Reduction conditions within the repository: During the lifetime of the containers, the repository environment will evolve from warm oxidizing conditions to an ambient temperature anoxic period. The oxidizing to reducing transition takes place over a relatively shorter time than the return of temperatures to ambient conditions which is expected to take thousands of years. The major source of oxidants in a repository is the oxygen trapped within the pores of the compacted buffer and backfill materials surrounding the container and within the partly saturated portion of the rock mass surrounding the repository (products of gamma radiolysis are another but minor source of oxidants). The amount of trapped oxygen decreases with time due to reactions with the container surface and with other materials in the repository such as the ferrous minerals in the backfill.

- Repository temperature: Corrosion rates, which generally decrease with decreasing temperature, depend on decay heat output, heat transfer rate and spacing of containers. As the repository cools with time, the rates of corrosion and mass transport processes (diffusion-driven with possibly a convective component) will decrease.

- Groundwater composition: Initially, corrosion will be limited because the buffer material near the container may dry out partially because of decay heat. Ultimately, the repository will become fully saturated and the ground water will induce local corrosion.

To minimize water-related impacts, one option is to site a repository in an arid desert region. This may not be a practical option for Canada because such regions are far removed from the locations where used fuel is generated. However, geological disposal within the stable granitic rock of the Canadian Shield, at a depth of 500 -1000 m, is considered to be generally acceptable for isolation of the Canadian used fuel [15,16]. Alternately, the repository may be located within a shallower clay layer in the sedimentary rock sequences overlying the granitic rock. Location of the repository in a geologically stable region ensures that the post-closure disposal system would be passively safe.

The design of a deep geological repository involves the provision of multiple barriers between the emplaced waste container and the geosphere. This results in a tortuous path for the flow of ground water to the waste container and subsequently from the waste container to the geosphere and eventually to the biosphere. In essence, slow ground water flow, along with radioactive decay, reduces the flux of radionuclides from the repository to the biosphere. A well-designed repository will result in acceptable future impacts to both humans and other biota. Typically, releases of radionuclides to the biosphere are not expected to occur for time periods in the order of tens of thousands of years.

Figure 5 illustrates the concept being developed for a deep geological repository in Canada [13].
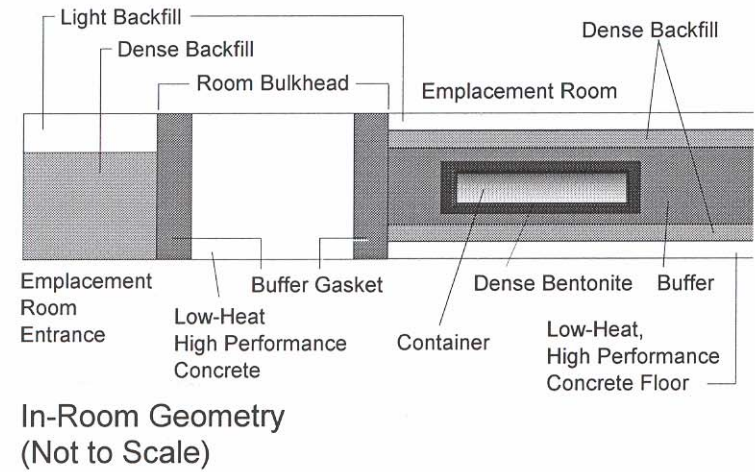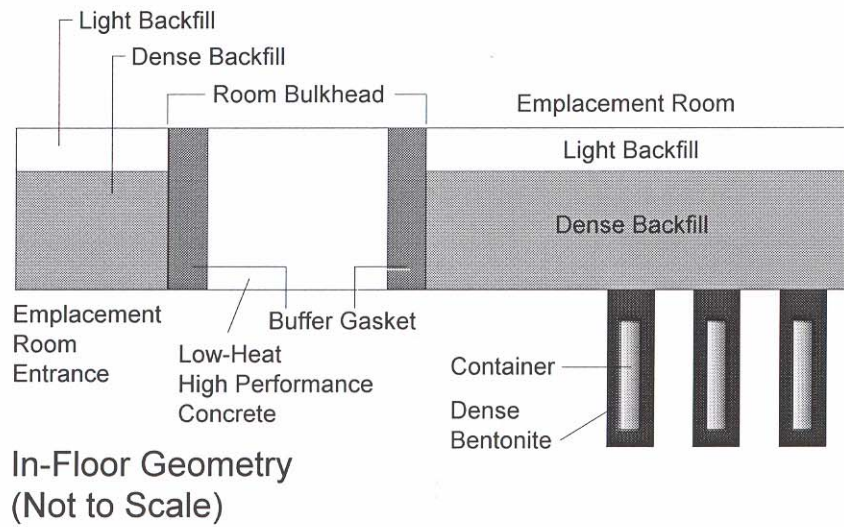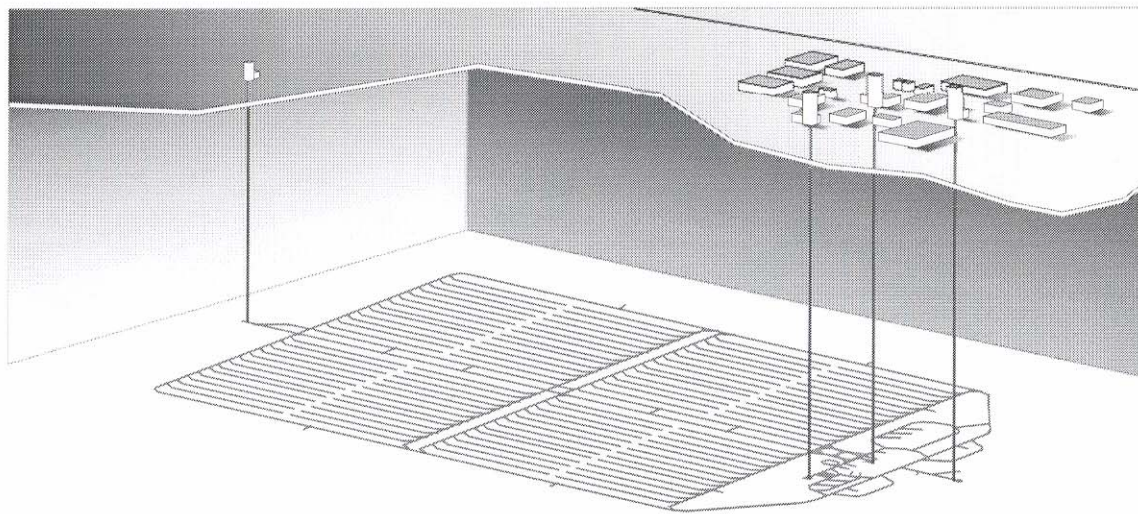
In-Floor Geometry
(Not to Scale)

In-Room Geometry
(Not to Scale)

Figure 5   Concept for a Deep Geological Repository in Canada

4.2 General Considerations for a Deep Geological Repository

To minimize future dose impacts from emplacing waste in a deep geological repository, the repository should be located in a tectonically stable and preferably, low permeability formation with reducing groundwater conditions. In order to satisfy the safety requirements of a deep geological repository, extensive geotechnical, engineering and safety assessment studies are required to identify a suitable repository depth, and adequate used-fuel container and sealing system designs [16]. Proper design of an engineered barrier system (refers to the container and sealants), would retard the transport of radionuclides out of the repository both by making the transport very slow (for example by diffusion) and also by enhancing the retention, via sorption and/or precipitation of radionuclides leached from the waste form.

The choice of repository depth depends on a large number of factors such as the fracture zone in the host rock, electrochemical and chemical conditions in the host rock, groundwater flow, and the thermal/mechanical/hydraulic impacts of the repository on the host rock. In general, the greater the depth, the greater the transport distance from the disposal rooms to the surface and the lower the likelihood of human intrusion and natural disruption. However, in-situ stresses and in-situ temperatures also increase with depth.

The used fuel container is an important component of the overall engineered barrier system. Its design depends on the environmental and mechanical conditions in the proposed repository. Containers represent a significant component of the overall cost of disposal. Therefore, for a given choice of the container material, there are practical limits on its wall thickness. Containers with a very conservative design, i.e., very thick walls, are difficult to fabricate and inspect. In practice, the choice of the container material and its designed corrosion allowance are dictated by the choice of the geological formation or geomedia in which the waste is emplaced and the choices made for the backfill and buffer materials. Rather than relying on a very conservative waste container design to achieve zero releases, reliance must be placed on the optimal integrated performance of the various components of the overall repository system in order to achieve non-zero but acceptable dose impacts.

Different types of sealants are required to limit the release of contaminants from a disposal repository. The buffer material, which surrounds the disposal container, limits container corrosion and hence the rate of waste form dissolution by inhibiting the movement of ground water near each container and by modifying its chemistry. Backfill sealants are used to fill the space in disposal rooms in order to keep the buffer and containers securely in place, to fill the space in tunnels and shafts in order to prevent access to the emplaced waste and to retard contaminant transport. Other sealants are used in conjunction with backfill materials to inhibit ground water movement in shafts and tunnels. Based on the above requirements, desirable characteristics of sealants include low hydraulic conductivity, adequate availability and predictable long term performance. Because of its low hydraulic conductivity, its near-neutral pH pore water and its ability to self-seal upon re-wetting, compacted bentonite clay is a favoured buffer material in the Canadian, Finnish, Swedish and Swiss disposal programs. Backfill materials may be either clay or cement based materials. Clay-based backfills are preferred for use in disposal rooms because of the desire to ensure a near-neutral pH environment near the containers.

4.3   Overall Requirements for Deep Geological Disposal Containers

A used fuel disposal container must provide containment for the used fuel over a specified period of time under the anticipated chemical environment and thermal, mechanical and hydraulic loadings in a deep geological repository. This requirement may be achieved by designing the container as a single vessel of a single material, or an assembly of two or more components with possibly dissimilar materials that provides the necessary corrosion barrier, structural strength, and internal support for the used fuel bundles.

The container will be loaded with used fuel at the aboveground packaging plant located on the disposal site. The loaded containers will then be transported to the underground disposal facility and emplaced in buffer material within the disposal rooms (the rooms would then be sealed with backfill material; see Figure 5). Thereafter, the container must remain securely in place and over its lifetime restrict access of ground water to the waste form.

Accordingly, a container must fulfil the following functions:

- It must provide containment for the used fuel from the time of loading, through handling, transportation and emplacement operations and for its design life during the post-closure phase of the repository.

- The container must provide adequate shielding to ensure that radiation fields at its surface do not adversely affect the performance of other engineered barriers.

Based on CANDU fuel characteristics and deep disposal in the Canadian Shield at a depth of 500-1000 m, key performance and design requirements for the used fuel container are [16-18]:

- The container should have a design life consistent with the characteristics of the geomedia in which it is emplaced so that the post-closure dose to members of the public/biota would be within acceptable limits.

- The total strain developed in any part of the container must not exceed the creep-rupture strain[12] of the material over the design life of the container. This is to ensure that the only failure mode for the container is via corrosion.

- Heat transfer characteristics of the container/buffer system must be such that the temperature of the fuel in the container does not exceed 170°C (to preserve integrity of fuel cladding) and the temperature of the outer surface of the container in the disposal room does not exceed 100°C (this avoids undesirable phase transformation of a bentonite-based buffer and would also avoid boiling of groundwater that comes into contact with the container surface).

- The container should withstand a load equivalent to the imposed external pressure. The latter is comprised of a hydrostatic pressure, a bentonite swelling[13] pressure (assuming bentonite clay is used as a buffer material) and a hydraulic pressure due to glaciation[14].

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[12] Creep-rupture strain refers to the maximum percent elongation of a metal specimen before it ruptures.

[13] Upon contact with water, bentonite clay will swell and thus exert a pressure on the container.

[14] Glaciation will result in formation of an ice cap on top of the repository; the ice cap is responsible for the hydrostatic pressure.

- The container should be able to withstand a rise in internal pressure from several potential sources, namely, gas production due to corrosion of internal components, release of fission product gas from the fuel, helium build-up from alpha decay of the fuel, and radiolysis of any residual water.

- The container must be designed to withstand seismic loads.

- The capacity of the container should be optimized considering factors such as thermal limits, container surface radiation fields and impact on the overall disposal cost. Its overall size must satisfy the requirements of the disposal systems including the selected emplacement method.

- The container design should limit the surface dose rate so that adverse impacts on the buffer material and the near-field water chemistry are avoided.

- The container should be designed to facilitate retrieval.

- The exterior surface of the container should be easily decontaminated. The method of decontamination should not impair the long-term performance of the container.

- The container should be designed for ease of inspection (defects and leak tightness).

4.4   Deep Geological Disposal Container Designs

4.4.1 Design Concepts for Used Fuel Containers

A number of container design concepts have been evaluated world-wide [16,18].

- Containers with Self-Supported Metal Shells

  These are required to be sufficiently thick to resist the external pressure. They may be constructed of a single corrosion resistant material or as a combination of two or more shells where the outer shell is made of a corrosion resistant material and the inner shells provide the structural strength.

  Containers fabricated from a single material such as copper or titanium would need to be at least 70 mm thick. Containers with such thick container walls are difficult to fabricate and inspect. The Swiss have studied a cast steel container with a minimum thickness of 150 mm in order to meet a container lifetime of 1,000 years.

  Dual walled designs investigated include combinations of a) titanium outer shell and carbon steel inner shell b) steel outer shell and cast iron inner shell and c) copper outer shell and carbon steel inner shell. The copper/steel vessel combination represents the current Canadian container design as discussed in Section 4.4.3. The higher strength of steel relative to that of copper allows the outer copper shell to be limited to 25 mm in thickness; without the inner steel vessel, the thickness of the copper vessel would have to be significantly greater than 25 mm.

- Containers with Internally Supported Metal Shells

  In this concept the outer, corrosion resistant metal shell is supported internally in order to resist the external pressure. Options investigated include:

  - A packed particulate container in which particulates, such as glass beads or sand, are compacted into the empty space after used fuel bundles have been placed in the container.

  - A metal-matrix container in which low melting point metal (such as lead) is cast to fill the empty space.

  - A structurally supported container in which internal structural support (array of carbon steel tubes) acts in combination with a compacted particulate.

4.4.2   Choice of Container Materials

The inter-relationship between the choice for the container material and the choice of the host geomedia is reflected in the diverse disposal programs adopted by various countries [18]. This is shown in Table 6. The attributes of several candidate used fuel container materials [19, 20] are shown in Table 7. Note the following:

- Clay has a swelling capacity, is self-sealing and has superior radionuclide retention properties compared to crystalline rock. Thus, a short-lived container constructed of iron or steel is compatible with clay, because the container in this system is not required to provide long-term containment.

  Because radionuclides are retained to a lesser extent in granitic rock than in clay, designs for waste emplacement in granitic rock rely on clay as buffer and backfill materials to retard releases.

- A short-lived container may be adequate for sparsely fractured rock; a long-lived container is, however, required for moderately fractured rock.

- A carbon steel container with 150 mm wall thickness would only have a 1,000 year life in a granitic disposal repository. Use of carbon steel containers in an extensively fractured geosphere would lead to unacceptably high doses; a sparsely fractured geosphere would be required to offset the short lifetime of a carbon steel container. Hence, selection of carbon steel as the material of choice would place significant limitations on siting flexibility and further introduces modeling uncertainties because of the need to consider hydrogen gas generation[15] and the transport of contaminants under gas-liquid flow.

- Copper is one of the choices for a long-lived container. Oxygen-free phosphorus-doped (OFP) copper has been identified as the corrosion barrier material in the Swedish, Finnish and Canadian disposal programs. Selection of this material in the Canadian disposal program would allow Canada to benefit from the experience gained in the Swedish and Finnish programs (these European repositories will be in service long before the Canadian repository becomes operational).

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[15] Exposure of carbon steel to low pH water leads to hydrogen gas formation.

Table 6   Concepts for Deep Geological Disposal in Selected Countries

Country	Type of Geomedia	Design and Engineered Barrier System
Belgium	Clay	• Used fuel/HLW in stainless steel over-pack. • Bentonite backfill. • Concrete liner. • Located several hundred meters below surface.
Canada	Granite	• Used fuel waste form. • Copper containers with inner steel vessel. • Bentonite buffer and backfill. • Waste in bore-holes or disposal rooms. • Located 500-1000 m below surface.
Finland	Granite	• HLW waste form. • Copper containers with cast iron insert. • Buffer and backfill. • Located several hundred meters below surface.
Japan	Crystalline or sedimentary rocks	• HLW waste form. • Steel overpack. • Bentonite buffer. • Waste emplaced in tunnels or bore holes.
Korea	Granitic rocks for HLW	• HLW waste form. • High nickel alloy, stainless steel or copper containers. • Waste emplaced in boreholes. • Bentonite buffer. • Located approximately 500 m below surface.
Spain	Clay, granite	• Used fuel waste form. • Carbon steel containers. • Bentonite buffer. • Waste emplaced horizontally. • Located approximately 260 m below surface.
Sweden	Granite	• Used fuel waste form. • Copper containers with cast steel inserts. • Bentonite and crushed rock. • Waste emplaced in bore holes. • Located approximately 500 m below surface.
Switzerland	Clay (granite basement)	• Used fuel /HLW waste form. • Steel canister. • Bentonite buffer. • Waste emplaced horizontally. • Located 500-1000 m below surface.
US	Volcanic tuff	• Used fuel /HLW waste form. • Nickel alloy container with inner stainless steel vessel. • Container covered with titanium drip shield. • Waste emplaced horizontally. • Located 200-500 m below surface in the unsaturated zone (300 m above water table).

Table 7   Corrosion Behaviour of Various Candidate Container Materials

Material	Attributes
Steel	• Carbon steel is considered as a corrosion allowance metal, which has a slow but measurable uniform corrosion rate. • Carbon steel corrosion would generate substantial quantities of hydrogen gas with possible impacts on repository performance. • Stainless steel is considered as a corrosion resistant material which has a very low corrosion rate; although the material is generally passive, i.e., it is protected by a surface oxide film, breakdown of this film can render the material susceptible to localized corrosion.
Copper	• Considered as corrosion allowance metal, which has a slow but measurable uniform corrosion rate. • Thermodynamically stable in pure water and will corrode only in the presence of oxidants. • Besides uniform corrosion, the only other plausible mechanism of corrosion is pitting; oxidants are required to maintain pit propagation. • Does not react to form hydrogen gas.
Nickel based alloys	• Considered as a corrosion resistant material, which has a very low corrosion rate; although the material is generally passive, i.e., it is protected by a surface oxide film, breakdown of this film can render the material susceptible to localized corrosion. • Susceptible to crevice corrosion and pitting. • Uniform corrosion rates for nickel based alloys are expected to be very low and comparable to those for copper and titanium alloys. • No technical difficulties are expected in terms of fabrication, inspection and closure welding. • Potential cost of container expected to be similar to those for copper or titanium alloy container. • A great deal of effort is required to develop good understanding of corrosion mechanisms and to evaluate performance in a repository environment.
Titanium alloys	• Considered as a corrosion resistant material which has a very low corrosion rate. • Although the material is generally passive, breakdown of the protective surface oxide film can render the material susceptible to localized corrosion. • Crevice corrosion might occur but its extent is controlled by the supply of oxygen. Also, radiation tends to repassivate the crevices, i.e., the corrosion may stop.
Ceramic	• Excellent corrosion resistance. • May be susceptible to cracking; structural performance characteristics require extensive investigations. • Fabrication techniques require extensive development.

• Compared to the use of copper, there are many uncertainties regarding the long term performance of titanium alloys; the choice of titanium, as the corrosion barrier material in the Canadian disposal program, would lead to a significant developmental cost that Canada would have to incur on its own.

• Compared to the design lifetime of 100,000 years for a 25 mm copper container, the predicted lifetime for a 6.4 mm thick titanium container is 1200-7000 years based on consideration of crevice corrosion and hydrogen induced cracking. Because of the relatively short life of the titanium container, its use would be limited to a sparsely fractured geomedia.

- Natural analogues[16] exist for copper in environments that are similar to geological disposal environments. These provide long-term data on the corrosion resistance of copper in a natural environment. In comparison, titanium alloys have a short industrial service history and no natural analogues.

- Stainless steel is susceptible to localized corrosion by saline ground water and hence would not be suitable for Canadian Shield applications.

4.4.3 Canadian Design

The reference used fuel container design, developed by OPG, has a minimum design life of 100,000 years. Based on its capacity of 324 bundles and a projected inventory of 3.6 million used fuel bundles for disposal, the emplacement rate, over a 30-year repository operational period, is about 370 containers per year. This is considered to be a very manageable emplacement rate [19, 21].

The design consists of an outer OFP copper corrosion barrier vessel, an inner carbon steel load-bearing vessel and a carbon steel fuel basket. Each basket, as shown in Figure 5 [13], consists of an assembly of carbon steel tubing in a closed packed arrangement.

After loading with fuel, the inner vessel is sealed in a dry inert gas atmosphere by bolting the inner steel lid in place. A copper lid is then welded to the outer copper shell using an electron beam. Since the welding is carried out under vacuum, the annular space between the inner and outer container shells will remain at vacuum although, over a long period of time, inert gas from the inner vessel may diffuse into this space. Finally, the container is encased in bentonite sleeves and then emplaced.

The overall container is illustrated in Figure 6 [13]. The dimensions of the overall container and other pertinent data [22, 23] are shown in Table 8. The copper corrosion barrier is designed to collapse onto the inner steel container under repository loading conditions and thereafter be supported by it.

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[16] Because of the long history of copper usage, artifacts of copper are found in nature; their condition offers insights into the corrosion behaviour of copper over geological time periods.

Table 8   Overall Design Data for OPG Used Fuel Container

Overall diameter of container	1168 mm
Overall length of container	3867 mm
Shell thickness of outer copper vessel	25 mm
Lid thickness of outer copper vessel	25 mm
Overall diameter of inner vessel	1116 mm
Overall length of inner vessel	3708 mm
Shell thickness of inner vessel	96 mm
Capacity of fuel basket	108 fuel bundles
Number of fuel baskets stacked within inner vessel	3
Overall mass of empty copper container (with lids)	3.8 Mg
Overall mass of empty inner vessel (with lids)	10.8 Mg
Overall mass of empty container	14.6 Mg
Overall mass of filled container	23.5 Mg
Maximum outer surface temperature of container	100°C
Minimum cooling time for used fuel	30 years

4.4.4 Other Designs

Because of the similarities in the Swedish, Finnish and Canadian disposal concepts [18], this section is restricted only to a comparative assessment of the differences in the disposal container designs developed by these three countries. In the Canadian design (OPG design), a steel vessel serves as the inner load-bearing component which differs from the cast iron insert used in the Swedish and Finnish designs. The cast iron insert is a cylindrical metal cast, which incorporates an array of cylindrical channels for housing the fuel bundles. Selection of the inner steel vessel in the Canadian design was based on a comparative assessment [22-24] of the suitability of this and the cast iron insert designs for housing CANDU used fuel bundles. The assessment indicated the following:

- While the inner vessel can be readily fabricated and inspected, there are significant uncertainties regarding the fabrication and inspection of cast inserts for the Canadian program. This is primarily because of the large number of fuel bundle channels required in the casting to house CANDU used fuel: based on the required emplacement rate, up to 60 channels are required compared with the 4 and 12 required in the Swedish and Finnish programs, respectively.

- For comparable fuel capacity, the inner vessel design for CANDU used fuel is smaller, lighter and less costly than the cast iron insert.
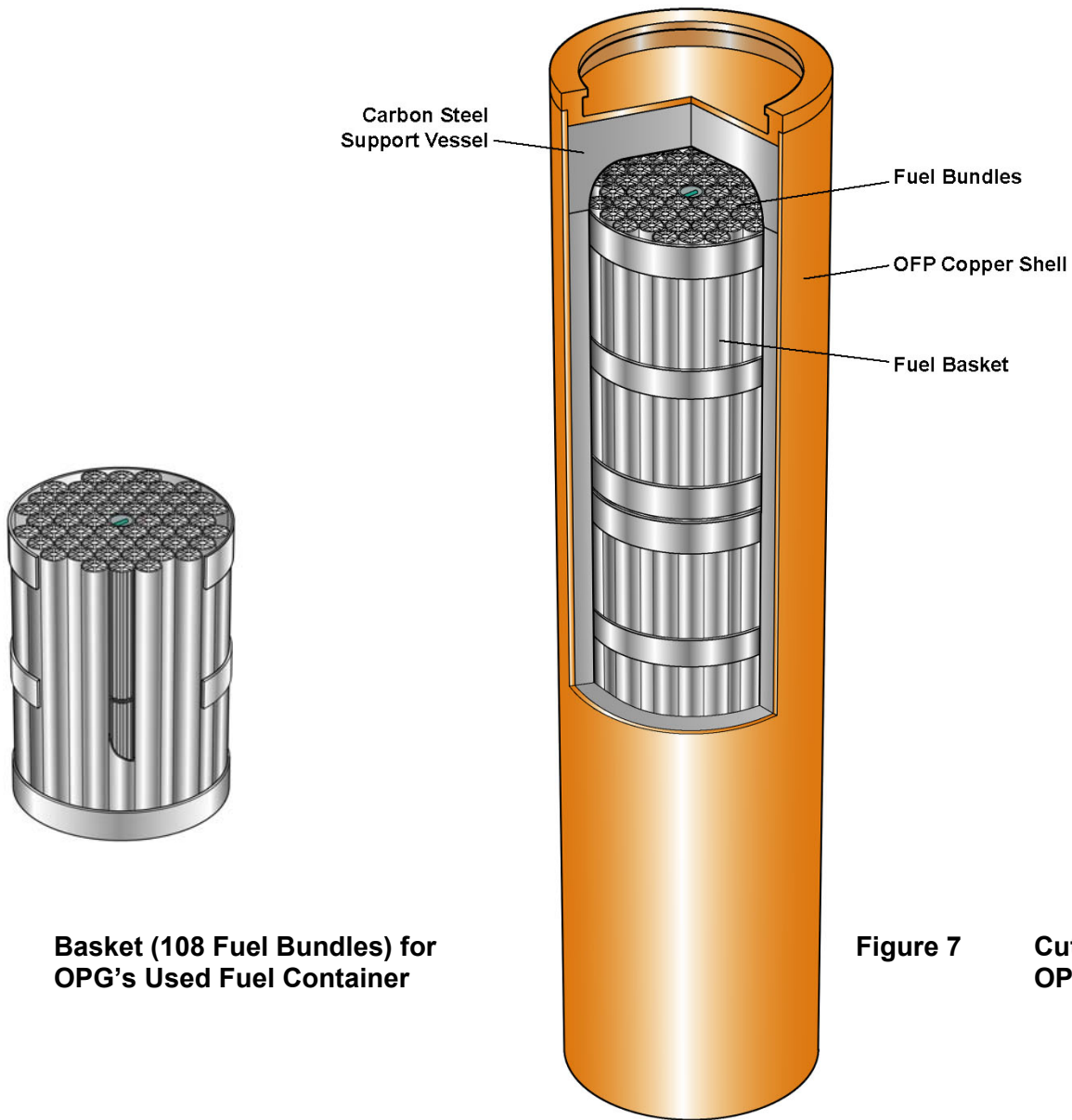
Figure 6   **Basket (108 Fuel Bundles) for OPG's Used Fuel Container**

Carbon Steel Support Vessel

Fuel Bundles

OFP Copper Shell

Fuel Basket

Figure 7   **Cut-Away View of OPG's Used Fuel Container**

- For CANDU used fuel, the inner vessel design leads to a significantly lower axial dose rate outside the container (lower by a factor exceeding 10 compared to the insert design).

5.0   CONTAINERS FOR TRANSPORTATION OF USED FUEL

5.1   Concept of Used Nuclear Fuel Transportation

Used fuel must be shipped to the central extended storage or disposal site in containers that shield, contain the radioactivity and dissipate the heat. Containers used for transportation are approved and regulated by the Canadian Nuclear Safety Commission (CNSC) through the Transport Packaging of Radioactive Materials (TPRM) regulations. These regulations are reflective of IAEA international standards. The TPRM regulations cover external radiation levels, allowable external surface contamination, permissible leakage of radioactivity in normal conditions, and retention of shielding capacity and containment of radioactive material in severe (impact and fire) accident conditions. These regulations are intended to reduce the exposure of transportation workers and the general public to a safe level.

Used fuel may be transported via three possible modes of transportation: road, rail and water. The risks associated with air transportation are considered to be too great. Shipment would only be along designated routes. For the purpose of this discussion, the short-distance transportation of the fuel from the generating stations to an onsite extended storage facility or the transfer of fuel receipts at the central storage or disposal facility to the emplacement location is considered to be outside the scope of this background paper.

The road transportation system consists of an engineered tractor/trailer/container system. The rail transportation system may consist of a dedicated train with several railcars, buffer cars, a caboose and a locomotive. The water transportation system may consist of an integrated tug/barge unit. The tug could transport either road or rail containers. The barge can be loaded to accommodate a cargo equivalent to several rail containers.

Transportation by road is subject to significantly more weight restrictions than transportation by rail or water. Road container packages[17] (including impact limiters) for LWR fuel typically weigh about 25 Mg and contain 1-2 Mg of used fuel while rail container packages weigh about 125 tons and transport 15-20 Mg of used fuel [25]. In comparison, the DSC package (including impact limiters), which can be transported by rail or water and possibly also by road, weighs 101 Mg and holds 10 Mg fuel while the IFTC road package weighs approximately 35 Mg and hold 5 Mg fuel. A larger rail IFTC weighs 77 Mg when fully loaded and holds 15 Mg fuel (contains 6 modules or 576 fuel bundles) [16].

The feasibility of larger shipments by rail and water suggests the potential for significant cost savings using these modes of transport. In the rail option, a road link to the railheads will still be needed. Similarly, although transportation via water offers the opportunity for a fewer number of shipments, the containers would still need to be unloaded and transferred from the docks by another mode of transport to the CESF or the disposal site. Transportation from the docks by rail would help to maintain the high volume shipment rate.

5.2   General Considerations for Used Fuel Transportation

Canadian used fuel may be shipped in existing transportable DSCs and in metal transportation containers. Unlike the DSCs, the metal containers are intended for repeat use. It is instructive

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[17] Packaging for transportation containers consists of impact limiters, impact armoring and attachments. In the event of an accident, the impact limiters are expected to crush and limit damage to the container and its contents.

to examine the activities associated with the repeat use of a metal transportation container [16, 26]. For example, typical activities associated with the transportation of used fuel between a nuclear generating station and a disposal facility are listed in Table 9. These activities define the functional requirements for the transportation container and for the interfaces at both locations.

Table 9   Activities Associated with the Use of a Metal Container Over a Transportation Cycle

Activities Upon Receipt at a Disposal Facility	• Inspect for damage and any evidence of leakage upon arrival at disposal facility. • Receive transportation containers at the packaging plant, unload the containers inside shielded cells, load used fuel inside disposal containers, and place each container in a shielded transfer container for emplacement. • Decontaminate transportation container in preparation for return trip to nuclear station.
Loading of Used Fuel at Nuclear Station	• Remove impact limiters. • Fill empty container with water, remove the container lid bolts, lower the container into the pool, and lift lid out and inspect. • Remove empty modules from container and replace with filled modules, reposition lid on container, and spray container with water as it is lifted out of pool. • Place container in the decontamination/preparation area, insert lid bolts and tighten. • Drain water inside container, insert drain plugs and leak test. • Attach IAEA safeguard seals. • Place container on trailer (in case of road transportation) and make tie-down connections.

ALARA[18] principles govern the radiation exposure during the various activities listed in Table 9. In addition, it is also important to ensure that exposures of those involved in the transportation as well as the exposure of the general public along transport routes are limited. In this regard, the IAEA regulations [27] or equivalently the TPRM regulations, which govern the packaging of transportation containers, specify the requirements for shielding, contamination and leakage control, marking, labelling and placarding. Additionally, a maintenance program must be specified in order to obtain a design approval certificate for a transportation container. This specifies the frequency of leak testing, the replacement schedule for seals and components such as bolts and plugs, and the inspection and polishing of the container surfaces to facilitate decontamination.

During transportation, a container will experience vibrations (e.g. as a result of uneven road surfaces) and acceleration (railcars would be suitably equipped to reduce the forces on the container resulting from normal train activities such as shunting). Prior to transportation, the container must, therefore, be fastened to either the trailer, railcar or barge cargo hold with a specially designed tie-down system. In the event of a severe accident, the tie-down system would release the container without affecting its shielding or containment integrity. In case of physical damage, the container may be taken out of service permanently.

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[18] As Low as Reasonably Achievable

5.3   Overall Requirements for Used Fuel Transportation Containers

Requirements for used fuel transportation containers are similar to some of the requirements for used fuel storage containers listed in Section 3.3. Additional requirements also arise from a consideration of the extreme weather conditions that can be experienced in Canada.

For transportation, used fuel must be appropriately packaged. Packages for transporting spent fuel constitute a Type B package[19] [27]. These packages must withstand the same normal transport conditions as Type A packages, but because their radioactive contents exceed the Type A limits, it is necessary to specify additional resistance against the release of radiation or the release of radioactive materials in an accident. The Type B package should be capable of withstanding expected accident conditions without breach of containment or without an increase in radiation level that could potentially endanger the general public and those involved in rescue or clean-up operations.

Testing under accident conditions is done to ensure that a container meets the above requirements. Details of the tests and the acceptance criteria with regard to leakage and radiation fields are prescribed in the IAEA regulations [27]. An outline of the required tests is shown in Table 10. The tests may be conducted using appropriate scale models of the package and/or using computational analyses. The severity of the acceptance tests, particularly those for accident conditions, indicate the high safety standards to which used fuel packages are tested prior to being deemed transportation worthy.

5.4   Used Fuel Transportation Container Designs

5.4.1   Design Concepts for Used Fuel Transportation

Design concepts pertaining to transportation containers [15, 28] are explored In this section. The reader is also referred to Section 3.4.1.

Overall designs for used fuel transportation containers should satisfy the following criteria:

- The container must be licensable as a Type B package under the TPRM Regulations,

- The container must be of optimal configuration and weight, and easily transportable,

- Loading and unloading of used fuel must be easily accomplished, and

- Occupational doses must conform to ALARA principles.

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[19] Generally, the primary assurance of safety during the transport of nuclear materials is the way in which the materials are packaged. Different packaging standards have been developed recognising that an increased potential hazard calls for an increased measure of protection.

Type A packages contain significantly lower levels of radioactivity than Type B packages. They are often small, often require little shielding and can be shipped under a general license. Type B packages require to be certified by appropriate authorities (CNSC in Canada).

Table 10   Test Requirements for Used Fuel Transportation Packages

Conditions	Tests
Normal transport conditions	• Water spray test: exposure to rainfall of approximately 5 cm/h for at least 1 h is simulated. • Free drop test: package is dropped a free distance of 0.3 m. • Stacking test: a compressive load, equivalent to 5 times the mass of the package, is applied. • Penetration test: a 6kg bar is dropped from a height of 1m on top of the package.
Accident transport conditions	• Free drop test: package is dropped a free distance of 9 m. • Penetration test: package is dropped a free distance of 1 m onto a rigid vertical bar. • Thermal test: package is exposed for 30 min to a hydrocarbon fuel/air fire with an average temperature of 800°C. • Water immersion test: package is exposed to a 15 m (minimum) head of water for a duration of 8 h (minimum).

The packaging system includes components that perform safety functions such as containment, shielding and assurance of sub-criticality and other components that aid in mitigating the effects of both normal and off-normal conditions on the safety function components. These other components include impact limiters, passive cooling systems and thermal insulation. Some of the main packaging system components are discussed below.

Containers may be made from either a single-walled (typically steel) or a multi-walled structure. The multi-walled containers are lighter in weight because they utilise materials such as lead which is an efficient gamma radiation shield with a density greater than steel. Further, the outer structural wall of a multi-walled container and the shock absorbing property of the intervening lead layer provides protection to the inner structural wall during a puncture impact. However, the design of a multi-walled structure using lead must consider factors such as the tendency for lead to flow as a result of the shock from a free fall of the container on an unyielding surface and the degradation in the shielding capability of the container due to melting in a fire accident.

A container may have single or double wall lids for its containment closure. The latter consists primarily of the cavity in which the contents are placed, the closure lids, the penetration closures and the seals. Both ends of the container may have lids to facilitate fuel-handling operations such as horizontal fuel loading and unloading. If possible, the closure lid should be recessed within the container end forging to avoid side loads on the closure bolts.

Because the metal surface is largely impervious, the performance of the seals in the containment boundary is a principal design concern. Seals for the closure lid may be metallic or elastomeric. The closure bolt load must pre-load the seal to prevent leakage. Metallic seals are more prone to transient loss of sealing during an accident because their deflection is less than that of an elastomeric seal. Closure seals are typically face-type seals in which an O-ring is compressed by the lid against a flat surface machined in the container end forging.

Containers for used fuel are equipped with a basket to hold the used fuel. Baskets provide structural support to the fuel assemblies, minimise contamination of the container cavity, contribute to the assurance of sub-criticality (neutron absorption), and have a role in maintaining

fuel and basket temperatures within allowable limits. Stainless steel alloys (for criticality control, boron is an alloying constituent of the steel used to fabricate LWR fuel baskets; it is not required for CANDU fuel baskets) are desirable structural materials for fabricating baskets. Baskets constructed from tubes are one of the simplest types. Basket structures may be fixed or removable.

Design of impact limiters are based on a balance between the stresses produced in the container and the available space for the impact limiters. They may be fabricated from crushable materials such as wood or foam. These materials must be contained within a ductile envelope.

Lifting trunnions may be external (typically round protrusions) or internal (pockets). Large containers are usually handled in the vertical position but are shipped in the horizontal orientation to provide acceptable package heights for bridge overpasses and tunnels. Rotation from the vertical to horizontal position may be achieved via rotation trunnions.

Insulation is required to protect the container from overheating during an accident. However, for normal conditions, it increases the difficulty in removing decay heat thus resulting in higher temperatures within the package. Enhancement in decay heat removal can be achieved by using surface enhancement techniques such as fins. Fins remove decay heat by a combination of conduction, convection and radiation.

Leak testing is required to verify the performance of the seals. Leak testing may be based on the detection of helium cover gas. Helium is a good heat conductor and is used to prevent fuel oxidation and hence preserve the integrity of fuel cladding material.

5.4.2 Choice of Container Materials

The selection of container material is based on factors such as shielding, structural strength, weight, ease of decontamination, availability and cost. Candidate materials for container designs include concrete, various types of steel, cast iron, depleted uranium and steel/lead or steel/depleted uranium combinations [15]. Concrete was discussed in Section 3.4.2; note the following regarding the other materials:

- Lead is a low melting, soft material with low structural strength; it cannot be used on its own and must be sheathed in steel.

- Stainless steel, either by itself or in combination with other materials, is a common choice for container design. For instance, the IFTC has a stainless steel wall with a thickness of 267 mm. Stainless steel is a readily available material.

- Steels and iron are less dense than lead and depleted uranium. Because density governs the material thickness required for radiation shielding, a stainless steel container is bulkier and heavier than an equivalent lead/steel container.

- Stainless steel has a high melting point and hence the material retains its structural integrity and shielding capacity under elevated temperatures, such as during a fire.

- Compared with ferritic grade steels and cast iron, stainless steel has better resistance to brittle fracture at low temperatures.

- Stainless steel is less susceptible to corrosion and is easier to decontaminate than other metals.

- The cost associated with a monolithic stainless steel container design is comparable to that associated with a laminated design (e.g. a combination of steel and lead). In terms of direct material costs, stainless steel is more expensive than ferritic steel. However, the fabrication[20] of ferritic steel containers entails additional costs: (1) ferritic steels must have a high alloy content in order to have resistance to brittle fracture at low temperature, equivalent to that of stainless steels, (2) a ferritic steel container must be heat treated, and 3) the ferritic steel container must be clad with stainless steel to facilitate decontamination.

5.4.3 Canadian Designs

Two designs exist for transporting Canadian used fuel, namely, the DSC and the IFTC. The reader is referred to Section 3.4.3 for a description of the DSC. The two transportation containers have significantly different designs. The DSC is a steel-lined concrete container, has a welded seal, is intended for single use only and has a design life of 50 years. On the other hand, the IFTC is a stainless steel container, has a bolted closure, is intended for repeat use and has a design life of 20 years [15,16]. One main disadvantage of the DSC is its relatively large weight; at present, it can be transported by rail and water only although transportation by road is considered to be feasible [26].

A brief description of the IFTC design is presented here. It is illustrated in Figure 8.

The IFTC has a rectangular base with dimensions of 1566 mm x 1881 mm; its height and wall thickness are 1697 mm and 267 mm, respectively. The container weighs approximately 28.3 Mg when empty and 33.3 Mg when fully loaded. A lid containing a Viton O-ring seal is bolted to the top of the container to form a sealed enclosure. The drain and vent openings also have Viton O-rings seals. For shipment, an impact limiter, weighing approximately 1.4 Mg, is bolted to the container lid; the impact limiter is constructed of blocks of redwood encased in a steel sheath. The container will be lifted and transferred using a specially designed lifting beam, which engages the two trunnions. The container would be transported on a flatbed trailer weighing approximately 10 Mg. The trailer has four axles, all with dual tires.

For rail transportation, a container with a capacity of 6 modules or 576 bundles has been described at the conceptual level in [16] – this design is not used in more recent studies. It weighs approximately 62 Mg when empty and 77 Mg when fully loaded. The rail container design has the same basic configuration as the road container but has an impact limiter at each end because of its larger size. The container would be transported on a rail flat car with 4 axles. The total weight of the full container and railcar assembly is approximately 111 Mg.

Road and/or rail containers would be used for water transportation.

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[20] A container may be constructed as a one piece casting, a single forging or a welded fabrication.

Impact Limiter

Trunnion
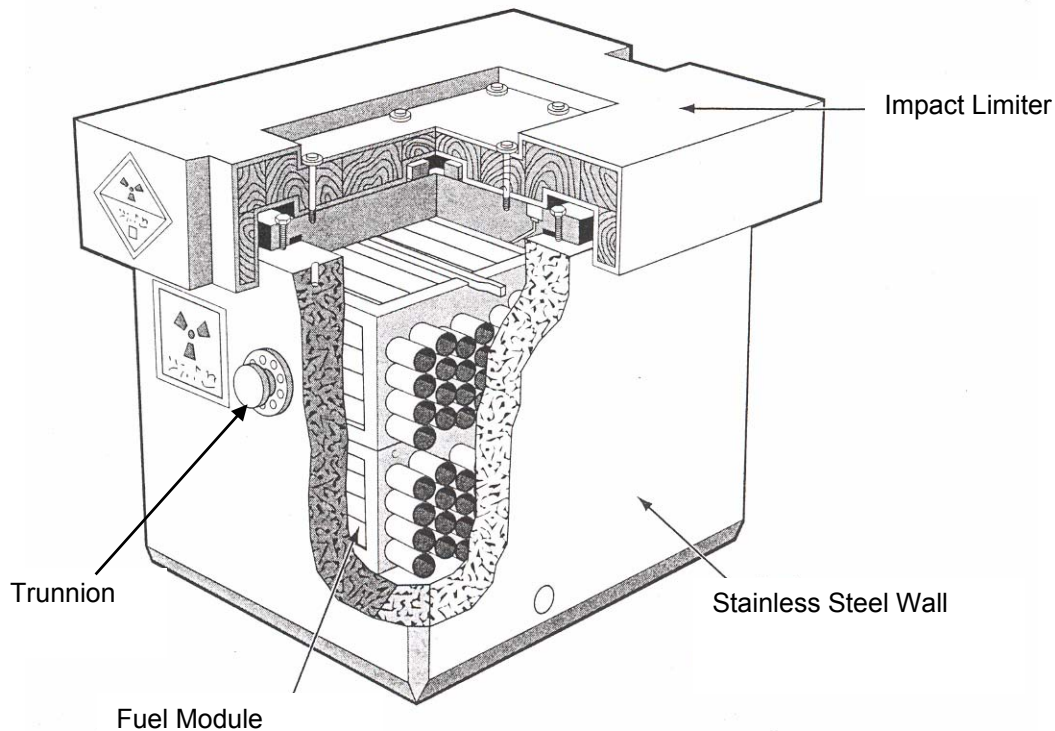
Fuel Module

Stainless Steel Wall

Figure 8   Ontario Power Generation's Irradiated Fuel Transportation Container

5.4.4 Other Designs

Figure 9 presents an illustration of a generic road container for LWR fuel [25]. It has a capacity for up to 4 PWR or 9 Boiling Water Reactor (BWR) fuel assemblies and weighs 25 Mg. The container's diameter is 1220 mm; the overall diameter and length of the container, including impact limiters, are 1830 mm and 6100 mm, respectively. The corresponding generic rail container has a capacity of up to 26 PWR or 61 BWR fuel assemblies and weighs 125 Mg. The diameter of this container is 2440 mm; its overall diameter and length, including impact limiters, are 3355 mm and 7625 mm, respectively.

Several vendors offer storage and transportation container designs for used fuel. Storage-only systems were briefly discussed in Section 3.4.4. Table 11 presents data on key features of two dual-purpose storage/transportation systems [14]. In general, these systems require the fuel to be cooled for 5-10 years before being placed in dry storage. Also, the fuel is typically stored within an environment of inert nitrogen or helium gas.
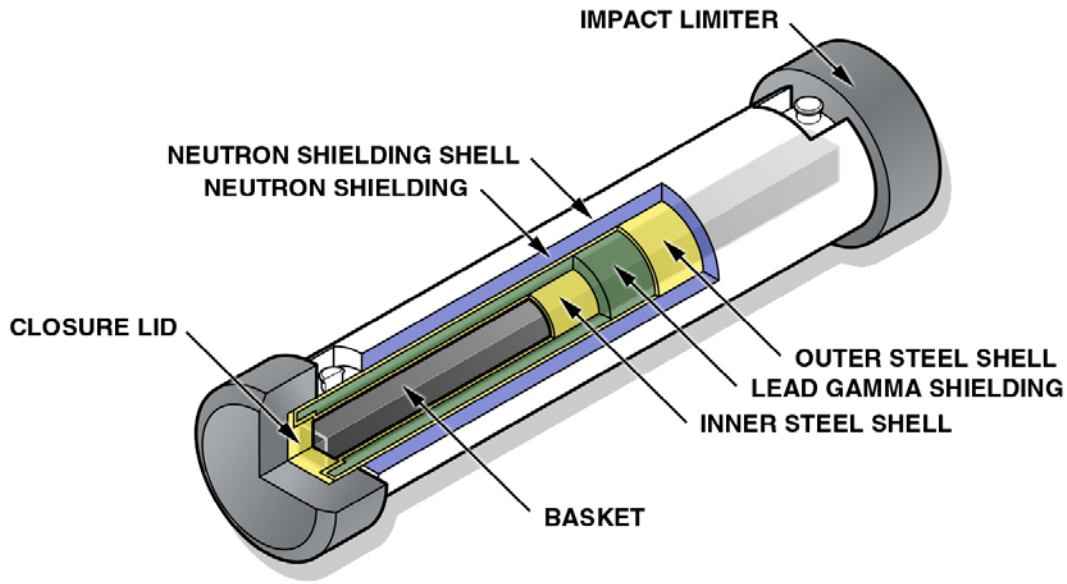
Figure 9   Cut-Away View of a Generic LWR Road Container

A comparison between the IFTC and containers for non-CANDU fuel is given below [15]:

- All containers for transporting used fuel are licensed as a Type B package.

- The majority of containers have impact limiters to protect the lid bolts during impact and to protect the lid seals in a fire.

- They have Viton elastomeric seals (because of Viton's excellent performance over a wide temperature range) and a double seal arrangement.

- Most containers have bolted lids and have a trunnion on each side of the container to facilitate handling.

- The IFTC (excluding the impact limiters) is manufactured from one material only, namely, stainless steel. The generic LWR container, illustrated in Figure 9, has lead sandwiched between its inner and outer steel shells. The generic LWR container also incorporates neutron shielding because of the enriched fuel used in a LWR.

- Similar to the IFTC, containers for Magnox and Advanced Gas Cooled Reactor (AGR) fuel are also rectangular in cross-section.   This is because the Magnox and AGR fuel have a short fuel element length (0.9 -1 m compared to 0.5 m for CANDU fuel and 4-5 m for most LWR fuel). Considering the short length of the CANDU fuel bundle and the rectangular shape of OPG's fuel modules (these have approximately equal height and depth), the choice of a cubic shaped container for used CANDU fuel, relative to a cylindrical container design for used LWR fuel, is optimal with respect to both the weight of the container and its manufacturing cost.

- The IFTC requires no fins to dissipate heat because used CANDU fuel is much cooler than used LWR fuel. The absence of fins facilitates decontamination and makes the container cheaper to manufacture.

- Because used CANDU fuel is cooler and, therefore, is less susceptible to oxidation, containers do not have to be vacuum-dried or purged of air to prevent fuel oxidation.

Table 11   Examples of Available Dry Storage/Transportation Technologies

System	Key Features
Hi-Star System *Offered by Holtec International, USA*	• System consists of a sealed stainless steel canister and a metal container. • Two systems are offered: HI-STAR 100 (larger) and HI-STAR 60 (smaller). • HI-STAR 100 holds 32 PWR or 68 BWR assemblies. • Canister has an outer diameter of 1740 mm and height of 4756 mm. • Container has an outer diameter of 2438 mm and height of 5080 mm. The wall is made up of layered carbon steel shells.
NAC-STC *Offered by NAC International*	• System consists of a stainless steel basket and a stainless steel/ lead/ stainless steel container body. • Basket holds 26 PWR assemblies. • Basket has an outer diameter of 1800 mm and height of 4178 mm. • Container has an outer diameter of 2510 mm and height 4902 mm.

6.0 CONCLUSIONS

Globally, used nuclear fuel is managed, on an interim basis, by storing it in water-filled pools and in dry storage structures. Depending upon the type of fuel and the design of dry storage systems, fuel must be cooled in pools for up to 10 years before being transferred into these systems. At present, dry storage presently about 17 % of the world's fuel storage capacity. Both wet and dry storage technologies are considered to be safe and mature technologies, which can provide adequate storage for at least 50 years.

Dry storage is a preferred option for extended storage because of its lower maintenance requirements, lower need for monitoring and lower overall cost. Further, the modularity of dry storage systems allows new capacity to be added in stages. Current dry storage technologies can be adapted for the extended storage of used fuel either at individual reactor sites or at a central site. Both above ground and below ground concepts are viable and involve proven container and vault technologies. Based on existing storage practices, it may be prudent to choose extended storage concepts, which allow the continued used of already filled DSCs. The remaining OPG fuel, which would be in wet storage, and all non-OPG fuel can be stored inside concrete vaults or inside self-shielded storage containers at the extended storage facility. Such containers will need to be designed and licensed. While it is considered feasible to increase the design life of current dry storage systems, it is likely that over an extended storage period, used fuel would need to be repeatedly retrieved and repackaged into new storage systems.

Geological disposal within the stable granitic rock of the Canadian Shield, at a depth of 500-1000 m, is considered to be generally technically acceptable for the safe isolation of the Canadian used fuel. The reference Canadian used fuel container design has a design life exceeding 100,000 years and a capacity of 324 used fuel bundles. Based on this design and the projected Canadian used fuel inventory, the required emplacement rate over a 30 year repository operational period is approximately 370 containers per year, which is considered to be a manageable proposition.

The current Canadian disposal container design consists of a copper corrosion barrier outer vessel and a steel load-bearing inner vessel. In practice, the choice of the container material and its designed corrosion allowance is dictated by the characteristics of the geomedia in which the waste is emplaced and the choices made for the backfill and buffer materials. In the absence of a specific site for a Canadian repository, the selection of copper as the outer container material represents a conservative design choice because copper is compatible with both granite and clay. The Canadian disposal concept is similar in several respects to concepts being developed by Sweden and Finland. Thus, Canada will benefit from the experience gained in the use of copper in the Swedish and Finnish programs.

Shipment of used fuel to either the central extended storage or disposal facility requires the use of transportation containers. These containers must conform to the rigorous requirements of a Type B package. The packaging consists of impact limiters, impact armouring and associated attachments. At the time of transportation, a significant portion of OPG's used fuel inventory will already be within the transportable DSCs. Therefore, it may be cost-effective to utilise them for shipment. DSCs can presently be transported by rail or water; however, transportation by road, despite their large weight, is also considered to be feasible. OPG's fuel inventory, that is not within DSCs at the time of transportation, as well as the non-OPG fuel basket inventory can be transported using a modified IFTC; the latter is a significantly lighter package compared to the DSC. Several other non-CANDU fuel transportation packages exist, but are not considered to be optimal for transporting CANDU fuel; this is primarily because of the much shorter length of CANDU fuel.

ACKNOWLEDGEMENTS

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