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NWMO BACKGROUND PAPERS
6. TECHNICAL METHODS

6-2 STATUS OF CENTRALIZED STORAGE SYSTEMS FOR USED NUCLEAR FUEL

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Hardy Stevenson and Associates Limited

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.

STATUS OF CENTRALIZED STORAGE SYSTEMS FOR USED NUCLEAR FUEL

October 2003

A BACKGROUND PAPER PREPARED FOR THE NUCLEAR WASTE MANAGEMENT ORGANIZATION (NWMO)

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SUMMARY

This document is a background paper on the status of centralized storage systems for used nuclear fuel prepared by Hardy Stevenson and Associates Limited for the Canadian Nuclear Waste Management Organization.

Centralized storage systems are storage facilities and associated systems to store used nuclear fuel in a central location. Producers of used fuel may build such facilities to provide effective management when they have many reactors producing used fuel. Often these are developed in a regional or a national context by the implementing organizations responsible for the management of used fuel.

Used fuel following its removal from the nuclear reactor is highly radioactive and is stored for about a decade in water pool storage facilities at the reactors. Following this period, it is easier to handle and transport used fuel and it can be stored away from the reactor sites. It could be stored either in wet storage (i.e. water pools) or in dry storage facilities, which could be built either at nuclear plant sites or at independent sites. Centralized storage becomes attractive as a storage option at this stage.

Used fuel management programs in twenty countries were reviewed. All the countries reviewed have centralized storage programs or plans to develop them. The review finds that centralized storage systems are already operational in twelve of these countries. Centralized storage is used over a wide range of circumstances from providing a common temporary storage for used fuel from a few reactors to providing a centralized management system for used fuel at the national level. It should be noted however, that at this stage of development, these should not be misinterpreted as long-term alternatives to disposal in these countries, although in many instances, they seem to provide the much-needed time for the development of long-term alternatives.

There are a number of technologies that are available for centralized storage of used fuel. These are water pools, metal casks, concrete casks, silos and vaults. Although several centralized water pools have been built, dry storage casks (metal and concrete casks) seem to be the most preferred option. While water pools do provide the most flexibility with regard to future options, dry storage casks provide the most advantage in terms of capacity building and require less care-taking than water pools. Storage systems have been built with these technologies and a significant amount of experience is available worldwide. Centralized storage systems could be built either above ground or underground and sited either at nuclear sites, at independent sites, or co-located with the reprocessing or disposal facilities. Above-ground systems seem to be preferred in most countries. There are suppliers who provide technologies as well as various storage services for these systems.

There are a number of situations faced by various countries that have influenced their decision-making with regard to the extent of centralization and selection of technologies for the management of used fuel. These are reviewed in detail in the report. Besides providing for the effective and centralized management of the used fuel, centralized

storage systems have been able to meet a number of needs, such as addressing the shortfall of storage space for used fuel at the nuclear plants, the need to remove used fuel from storage systems at the plants at the time of decommissioning, and the need to efficiently manage the used fuel until a facility is available for long-term management of used fuel. The role of centralized storage in the management of used fuel has been evolving over years and is considered in some countries as a technology for providing an alternative to disposal.

Current technologies for centralized storage systems were initially developed for an interim storage period of about 50 years. Many countries are now considering longer storage periods of 50-100 years.

Due to increasing used fuel inventories and either delays or lack of public acceptance of the disposal option, extended storage of used fuel is being reviewed as a long-term management alternative in a number of countries. Although not defined specifically, extended storage could typically encompass timeframes of 50 to 300 years. Long-term centralized storage is a potential management option for extended storage.

For these extended storage periods, the storage systems may need more research and development, particularly in terms of durability of used fuel and storage structures, conditioning of used fuel to assure containment of radioactivity, and cost-effective designs suitable for the long term. Such programs are taken up in a number of countries and in co-operative research programs of the IAEA.

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INTRODUCTION

This is an NWMO Management Systems background paper providing a general description of the centralized storage approach for used nuclear fuel (also known as spent fuel in many countries). It specifically reviews the status of centralized storage systems for used nuclear fuel. Centralized storage systems are defined here as storage facilities and associated systems that receive and store used fuel in a central location, often in a regional or a national setting.

Approaches for managing used fuel

Management systems are required for used nuclear fuel to ensure that humans and the environment are protected from the hazards it may pose.

There are several approaches for managing used nuclear fuel. The key approaches are:

1. Storage. In this approach, used fuel is stored in at-reactor storage, away-from-reactor (AFR) storage or centralized storage facilities.
2. Reprocessing. In this approach, used fuel is treated to remove and recycle most of its nuclear materials back in to nuclear reactors.
3. Long-term approaches to managing used nuclear fuel or nuclear wastes from reprocessing. These consist of extended storage of used fuel or nuclear wastes in long-term storage facilities and deep geological disposal.

The option of partitioning and transmutation of the reprocessed waste is being researched in some countries to assist long-term management.

The above approaches are used in several ways beginning with the discharge of the used fuel from reactors and leading to its long-term management (Fig.1). In the Canadian context, it should be noted however that reprocessing and partitioning and transmutation of the reprocessed waste are not considered, as Canada has no policy for reprocessing.

Other options such as disposal into space, under ice sheets, and in the ocean floor are not seriously considered due to technological, social and economic considerations.

> ***At-reactor storage***. The storage of used nuclear fuel is a fundamental need in the management of used fuel. Used fuel following its removal from the nuclear reactor, is highly radioactive and as a result requires cooling and shielding. It is therefore stored for the initial few years (for about a decade) at the reactor in pool-type storage systems where the used fuel is adequately cooled and shielded. This type of storage is integral to the operation of the nuclear plants in that it is located inside the nuclear plant and serves as a receptacle for used fuel immediately after it is discharged from the reactors.
>
> ***Away-from-reactor (AFR) storage***. Away-from-reactor storage systems are built either on-site (i.e. at the nuclear plant site) or at independent sites. These could be either wet storage facilities (i.e. water pools) or dry storage facilities. These systems provide for the

storage of used fuel when the at-reactor storage is filled to capacity. Used fuel is transferred from the at-reactor storage facility to these facilities so that storage space continues to be available for the freshly discharged fuel at the reactor. The term Independent Spent Fuel Storage Installations (ISFSIs) is being used in some countries, particularly the U.S., for AFR storage systems. In Canada, the AFR dry storage facilities are built at the nuclear plant sites and are generally referred to as on-site storage.

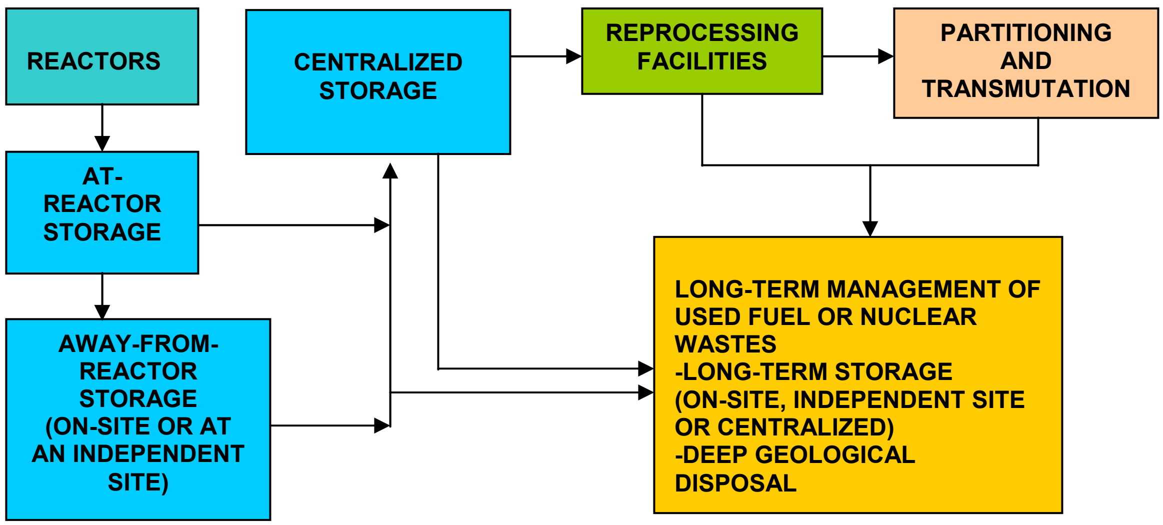


Figure 1. Various approaches in the management of used fuel

Centralized storage. Centralized storage consists of facilities used to store used nuclear fuel in a central location. These could be wet or dry storage facilities. Producers of used fuel generally build such facilities to provide efficient and cost-effective management when they have many reactors producing used fuel. Often these are developed in a regional or a national setting by the implementing organizations responsible for the management of used fuel. While AFR storage generally provides for storage for a single nuclear plant, centralized storage could provide for storage for used fuel from several at-reactor and AFR storage facilities.

Reprocessing. In this approach, fissile materials (plutonium and uranium) are chemically separated from the used fuel for recycling as fuel in reactors. The remainder of the used fuel normally in the form of liquid waste following reprocessing is known as high-level waste and is vitrified (i.e. solidified in glass) for eventual disposal. Many countries, including Canada, do not reprocess their used fuel for various reasons such as economics and policies on non-proliferation of nuclear weapons.

Long-term storage. This approach consists of storage of used nuclear fuel or high-level waste for an extended period with the intention of future reuse or disposal. On-site, independent site, or centralized storage facilities could be used with technologies that are suitable for such an approach. Such facilities do not provide a permanent or 'walk-away' type of solution; however, they do provide a long-term management alternative with continued monitoring of the used fuel or the nuclear wastes.

Deep geological disposal. This step involves conditioning (or containerization) of used fuel or the vitrified waste from reprocessing and its isolation in a deep geological repository without the intention of retrieval. Deep geological disposal facilities have been under development for over two decades. No deep geological disposal facilities have yet been built for either the used fuel or the high-level waste.

Partitioning and transmutation. In this emerging technology, the liquid waste from reprocessing is further processed chemically to isolate the long-lived hazardous isotopes. These isotopes are then transmuted to non-hazardous nuclides by bombarding them with nuclear particles in accelerators or special-purpose reactors. This technology has not yet been proven.

Of the above approaches, storage is considered as an interim approach encompassing a period of about 50 years, although of late, a number of countries are considering longer timescales of 50 to 100 years due to delays in developing long-term approaches. In countries that reprocess used fuel, storage time frames are minimized as reprocessing is carried out following a few years of fuel storage. Long-term approaches consider much longer time frames for the management of used fuel than those for interim storage.

Centralized storage systems

Individual producers of used fuel (i.e. utilities) could build centralized storage systems to meet their own needs if they have many reactors. They could also be built as local, regional, national or even as multi-national solutions to the management of used fuel by appropriate authorities in their jurisdictions. Existing AFR storage systems, either on-site or at independent sites, could also be used if warranted to provide for centralized storage for several reactors from various sites. With necessary development, it appears that centralized storage systems could be used for storage of used fuel for an extended period.

The need for storage has been increasing over the years as it continues to be the primary approach for the interim management of used fuel. Worldwide, about 8,000 tHM (tonnes of heavy metal, i.e. uranium) are placed in storage each year. As of the end of 2001, about 150,000 tHM have been stored in various types of storage facilities [1].

In Canada, 34,000 tHM of used fuel are in storage, comprising of 23% of the world inventory of used fuel. The Canadian reactors (known as Canadian Deuterium Uranium or CANDU reactors) use nuclear fuel made of natural uranium and as a result produce three to four times the amount of fuel produced in most other reactor systems which are fuelled with enriched uranium.

Many countries produce electricity from nuclear power with an open cycle (i.e. without reprocessing), resulting in an overall increase in used fuel inventory in the world. Worldwide, about a quarter of the used fuel inventory is being reprocessed (about 2500 tHM/year). A number of countries (mainly Belgium, France, Germany, Japan, Switzerland, Russian Federation and the United Kingdom) are recycling the fissile materials in their reactors thus slowing down the growth of used fuel inventory requiring storage while increasing the amount of vitrified wastes [2]. Some countries have ceased or are planning to cease reprocessing once their existing contracts run out (such as United States and Spain which have ceased to reprocess and Belgium which is considering the no-reprocessing option). Furthermore, many countries are following a trend toward deferred decisions with regard to disposal due to lack of public support and other domestic reasons. Long-term alternatives to disposal are also being reviewed in many countries with a view to find the most appropriate long term approach, as is the case, for example, in France and Canada.

The net effect will be an overall growth in the world's storage requirements. The total amount of used fuel in storage is expected to reach about 300,000 tHM in the next twenty years [1]. With the above outlook, centralized storage is expected to play an increasing role as a means to achieve economical management of used fuel.

STATUS OF CENTRALIZED STORAGE SYSTEMS

In this background paper, we review centralized storage as a management system for used fuel. It is often not clear what centralized storage implies and what its boundaries are. Here, we have reviewed centralized storage in its broadest sense, from systems that are used to manage used fuel temporarily from a few reactors to systems that are fully centralized, such as in a national context, to provide a management solution designed to function for extended timeframes, i.e. for many decades. We have discussed various dimensions of the centralized storage issue, from technical to various related aspects such as site selection, public acceptance and organizational issues. We have reviewed the data and experience of a number of countries and have assessed the outlook in those countries.

Centralized storage as a management system

By definition, centralized storage implies a system in which storage is provided at a central location rather than at a number of sites. As such, where centralized storage is used, it has reduced or even eliminated the need for a number of on-site or independent AFR storage facilities.

Storage capacities at the reactors are generally limited. In the past, the shortage of storage capacities was managed by increasing storage densities at the reactor pools by the use of tighter arrays (known as re-racking in some countries) for storing used fuel. But these measures have now been largely exhausted at these reactors and the utilities are faced with the need for building additional storage facilities before the reactor pools are filled to capacity. The need for additional storage has increased in recent years not only due to ongoing operation of reactors but also due to improvement in their operation, and reactor rehabilitation initiatives. Additional storage also becomes necessary where there are plans to decommission the reactors. Away-from-reactor storage either at the nuclear plant sites or at independent sites, rather than centralized storage, has become the expedient option for providing this storage.

In cases where there are a number of plants requiring such storage, or where there are a number of utilities involved, the centralized storage option is seen to be viable in terms of efficiency and cost effectiveness. Many such facilities have been built in various countries. The advantage of centralization is balanced against other issues such as the transportation of used fuel, and public acceptability.

Due to increasing used fuel inventories and either delays or lack of public acceptance of the disposal option, extended storage of used fuel is being reviewed as a long-term management alternative in a number of countries. Although not defined specifically, extended storage could typically encompass 50 to 300 years [1]. Centralized storage becomes a potential management option in such a context subject to further development of technologies and a commitment to continued monitoring of used fuel.

While any storage system that provides for common storage from more than one reactor can be called centralized storage, the benefits of centralization are maximized when such facilities fully function as centralized storage for all reactors in a region or in a country. This calls for co-operation among organizations producing used fuel, legislative and policy initiatives at the governmental levels and public support. Only one country (Sweden) adopted a national centralized used fuel storage policy, to start with, in lieu of AFR storage facilities and has a below-ground water pool type facility (CLAB), operating since 1985. Most countries adopted centralized storage as an adjunct option when and where it suited them and to the extent that centralized storage was needed.

Multi-national centralized storage systems are also potential alternatives with increasing international cooperation, economic globalization and market trends in this direction. The 2001 IAEA Joint Convention recognizes for example that safe and efficient management of used fuel might be fostered through agreements among countries to use facilities in one of them for the benefit of the other [3]. Out of necessity, reprocessing facilities provide such systems for their international customers for storing their fuel prior to reprocessing, albeit on a temporary basis.

In reviewing the current status of centralized storage systems, we focus on the following five questions:

1. What role does centralized storage play in the management of used fuel in various countries?

2. What technological options are available for centralized storage and what is their development status?

3. What are the specific considerations in bringing centralized storage into service?

4. What institutional frameworks are necessary for the management of centralized storage?

5. What are the current developments that may influence the future of centralized storage?

Role of centralized storage in various countries

The role of centralized storage in the management of used fuel differs from country to country. Centralized storage systems differ in terms of storage policy, site selection, facility size, and management and institutional issues particular to centralized storage.

Centralized storage facilities make use of technologies similar to those for AFR storage. The countries have chosen various technologies to fulfill the role of centralized storage depending on their requirements. There are no limitations on the number of technologies, as some countries find it convenient to transfer existing storage systems (such as different types of storage casks) to a centralized facility to minimize handling. Since the facilities are built away from reactors, transportation systems become a vital link to move used fuel to these facilities. Off-site transportation has been a significant consideration as well as a formidable task in some countries due to public opposition.

Common to most situations, however, the centralized storage systems essentially consist of the following features:

- Storage facilities with throughput and operating schemes matched to expected used fuel that is required to be stored;
- A modular approach to capacity building and for planning future extensions;
- A single-use land area to accommodate storage facilities and various infrastructure;
- A transportation system consisting of containers, vehicles and routes;
- Various other infrastructures such as systems for fuel handling and preparation of containers for storage.

A number of countries have adopted centralized storage to some extent if not fully depending on circumstances. A number of countries are also pursuing centralized storage as a future option. These are discussed later. In establishing a role for centralized storage, there is a plethora of situations faced by various countries with regard to management of used fuel. For example:

- Some countries had either expectations or definitive policies and plans for disposal, limiting additional storage that would have been otherwise required. However, disposal programs suffered major delays and setbacks resulting in a need to review management options for used fuel (e.g. Canada).
- Many countries have adopted a "wait and see" policy for disposal and are faced with the prospect of indefinite storage (e.g. Spain and United Kingdom).
- Several countries have made a long cooling period (50 to 60 years) a design consideration in developing disposal facilities requiring storage over a longer period (e.g. Belgium).
- A few countries are actively planning for long-term storage on the assumption that better options will emerge in the future. Some are pursuing the technology of partitioning and transmutation (P&T). In view of the large lead-time and uncertainties involved, these countries may also face the prospect of storing the used fuel for very long periods.
- Some countries have been faced with the need for increased storage, as traditional arrangements for used fuel were lost either due to political factors (e.g. countries that separated from the former Soviet Union could not ship their used fuel to the Russian Federation) or due to the cessation of reprocessing activities (e.g. U.S.).
- Political and public acceptance factors have influenced decisions on centralized storage in some countries. In the U.S. for example, the Nuclear Waste Policy Act of 1982 required Federal Department of Energy (DOE) to develop a centralized Monitored Retrievable Storage (MRS) facility to provide interim storage until a

deep geological repository is brought into operation. DOE developed a proposal but revoked it due to political and public opposition in the State of Tennessee, where it was to be built. A privately owned MRS is now being pursued by the nuclear industry [4].

For countries that traditionally reprocess their used fuel, the natural focus is storage of vitrified high-level wastes from reprocessing. For these countries, centralized storage of such wastes at the reprocessing sites becomes a logical extension of their management strategy pending disposal. However, they also require temporary wet storage at the reprocessing facilities for used fuel. Such facilities provide a centralized storage function for used fuel received from customers for reprocessing. Examples are the Sellafield reprocessing facility in the United Kingdom and the La Hague facility in France. This strategy is not available for Canada as discussed earlier.

Among countries developing disposal, there is an emerging trend to modify the disposal concept to include retrievable storage until such time that long term issues of safety and public acceptance of disposal can be fully resolved. Such plans generally consider conditioning of used fuel using containers that are suitable for disposal and its storage at the disposal facility. Some would argue that such storage becomes a variation, albeit a weak one, of the centralized storage option. This ultimately facilitates disposal as radioactivity significantly diminishes in the fuel and pre-disposal operations such as transportation and conditioning are completed well in advance of disposal. A number of countries are currently reviewing provisions for retrievable storage in their disposal programs (e.g. Germany, Sweden, France). Retrievable storage has already been made a requirement of disposal programs in many countries (e.g. Finland, Switzerland, USA)[5]. Canada is studying a modified disposal concept addressing these issues and based on the deep geological disposal concept developed by Atomic Energy of Canada Limited (See Annex for more information).

The role of centralized storage in various countries should be viewed in the light of their own circumstances. Twenty countries with significant programs for used fuel management were reviewed for their interest and involvement in building centralized storage. Of the countries reviewed, twelve countries already have centralized storage to some extent, while the remaining are considering plans to incorporate centralized storage into their programs sometime in the future. Here are some examples:

- As mentioned earlier, only Sweden has adopted centralized storage as a national policy; and a centralized water pool facility was built as early as 1985. Early development of organizational systems (e.g. utility-owned implementing organization called Swedish Nuclear Fuel and Waste Management Company or SKB) led to necessary decisions and early focus towards centralization in Sweden. Besides at-reactor pools, no other AFR storage has been built or committed to in Sweden. The centralized facility is now being expanded to meet its projected need for storage until disposal [6].

- Some of the largest centralized wet storage facilities are at the various reprocessing sites. For example, among the countries reviewed, the reprocessing facilities at Sellafield in the United Kingdom and at La Hague in France have built large centralized storage facilities both for used fuel and for vitrified waste from reprocessing. These facilities provide centralized temporary storage to their national and international customers. Japan has a similar facility at its Rokkasho Mura reprocessing plant for its national customers. The Russian Federation has a centralized wet storage facility at its Karsnoyarsk reprocessing site [1].

- The reprocessing facilities operated by Nuclear Fuel Services at West Valley, New York and GE at Morris, Illinois, both in the U.S., also provided centralized storage facilities for the U.S. reprocessing customers until the late seventies. With the 1977 ban on reprocessing in the U.S., these facilities stopped providing for storage and the fuel was returned to its owners. GE attempted to make its Morris, Illinois reprocessing facility commercially available for centralized storage with only a limited success. Some used fuel continues to be centrally stored both in wet and dry type storage facilities at this site [4].

- There are a number of facilities that provide some degree of centralization for used fuel from various reactors either at a nuclear plant site where the reactors are located, or at other sites. Bulgaria, Canada, France, Germany, Japan, and the U.S. are some examples. For example, in Canada, two waste management facilities (WMFs) at Pickering and Bruce provide centralized storage for two nuclear plants at each site, with four CANDU reactors at each plant. It should be noted however, that these are not considered as "centralized long-term storage" in the sense of the Canadian Nuclear Fuel Waste Act.

- A number of countries are planning national centralized storage facilities as the current facilities get filled. Bulgaria, Czech Republic, Germany, Republic of Korea, Russia, Slovakia, Spain and the U.S. are considering such facilities.

- France is considering centralized long-term storage of its used fuel in disposal-ready containers for up to 300 years. Five concepts using wet and dry storage both above ground and underground are being studied. The concepts consist of a modular surface facility, surface and semi-underground concrete bunkers, a semi-underground air-cooled concrete bunker, and a sub-surface facility consisting of a network of underground storage galleries [7].

- Several countries that are developing disposal technology are reviewing retrievable storage at the disposal facilities (e.g. Sweden, US) although the intention is permanent disposal. Centralized storage facilities and their eventual conversion to disposal following a phase of monitoring and integration of scientific advances have been suggested in the Canadian program [8].

A number of major international programs with centralized storage are reviewed below and the role of centralized storage in these countries is summarized.

Belgium

Belgium has 7 Pressurized Water Reactor (PWR) type power reactors (5.7 GWe), which are to be shut down by 2025. The Belgian policy has been to reprocess its used fuel and centralize the management of all its radioactive wastes until disposal in a deep geological repository. A direct disposal option for used fuel is also being considered when the existing reprocessing contracts run out [5]. In line with this policy, Belgium has followed a centralized storage program for its high-level wastes from the nuclear program for a period of 50 years.

At its Mol-Dessel nuclear plant site, centralized storage facilities were commissioned in 1996 for vitrified reprocessed wastes. The facilities for low and intermediate level wastes are also co-located at the Mol-Dessel site. As such, Belgium may include centralized storage for its used fuel at its Mol-Dessel site to the extent required for its non-reprocessed used fuel.

Belgium is planning for disposal but has not put a firm timetable for disposal at this time.

Canada

Canada has 22 CANDU power reactors, with a 15 GWe total capacity. It has been storing used fuel in water pools at the reactor sites. Dry storage systems have been developed and are being used for the continued storage of used fuel pending decisions on the long-term management of the used fuel.

In Ontario, where 90% of the nuclear power is produced, there are two four-unit nuclear generating stations at Pickering, another two four-unit nuclear generating stations at Bruce and a single four-unit station at Darlington. Eight reactors temporarily shut down at the Pickering and Bruce sites are to be brought back into service. In addition to large at-reactor wet storage facilities, there are two dry storage facilities, one at the Pickering plant site and the other at the Bruce plant site, owned by Ontario Power Generation (OPG), each providing on-site AFR storage for eight reactors with a combined storage capacity of 1.23 million bundles (about 25,000 tHM). Another on-site storage facility is planned at Darlington for used fuel from its four reactors. Although these facilities are recognized as on-site storage facilities, they do in fact provide centralized storage for all the reactors at each site. The utility did not find clear advantages in its studies carried out in 1979 in further centralization (i.e. a single facility for all sites) from engineering, safety or economic considerations (See Annex for more information on the Canadian program)[8].

The on-site storage facilities house OPG's own design of Dry Storage Containers (DSCs), which are reinforced concrete containers, each storing 384 CANDU fuel bundles [9][10].

Atomic Energy of Canada Limited (AECL) developed Concrete Canisters, which have been used to store used fuel from several early reactors. AECL has developed two modular dry storage systems CANSTOR and MACSTOR for CANDU and Light Water Reactor (LWR) fuel respectively. Concrete Canisters are being used for on-site storage at the New Brunswick Power's Point Lepreau plant [11]. Hydro Quebec's Gentilly-2 nuclear plant uses the CANSTOR design for its used fuel storage. AECL is seeking marketing opportunities for its MACSTOR design [12]. These facilities provide for on-site storage.

The Nuclear Fuel Waste Act (NFWA, 2002) has mandated the Canadian Nuclear Waste Management Organization (NWMO) to study three specific options, namely, deep geological disposal, long-term centralized storage and long-term storage at the reactor sites [13]. These studies are currently in progress. The studies include among other things: durability of dry storage systems, integrity of used fuel in the long term, conceptual designs and cost estimates for centralized storage and a modified deep geological disposal concept. Since there are no plans to reprocess used fuel in Canada, these options will continue to get increasing attention as long-term used fuel management options.

France

France has 58 PWR type reactors and one Fast Breeder Reactor (FBR) with 63.1 GWe generating capacity. It reprocesses its used fuel promptly and therefore requires only temporary storage of used fuel at the reactor sites. After two years of cooling, the used fuel is transported to the La Hague facility where it is stored prior to reprocessing in large stainless steel lined storage pools. Reprocessing wastes are also stored in storage systems at the facility.

France has also developed a centralized dry storage facility (CASCAD facility) at Cadarache for used fuel that is not reprocessed right away. This facility has a limited capacity of 100 tHM. Used fuel is loaded into canisters at the reactor sites and transferred to this dry storage facility. Used fuel is stored in storage wells at this facility and is naturally cooled.

The 1991 French Law stipulates the investigation of long-term centralized storage of its radioactive wastes, which will include used fuel that will not be reprocessed. The French Atomic Energy Commission (CEA) is investigating a centralized water pool facility for use over a period of 25 years, to be followed by a centralized long-term dry storage facility where the used fuel will be conditioned using canisters and stored for about 300 years. Conditioning processes and long-term storage in surface facilities are being studied for reprocessing waste. The feasibility of retrievable storage in deep geological formations is also being investigated [1][7].

There are no decisions made with respect to disposal.

Germany

In Germany, there are 19 operating LWR reactors (21 GWe) and 18 reactors that have been shut down. The spent fuel is initially stored in water pools at the reactors. Storage in dry storage casks is also licensed at the reactor sites.

There are three storage sites in Ahaus, Gorleben and Greifswald, providing a total storage capacity of 8345 tHM in Germany. In future, the plans are to store all the fuel in dry storage casks in a centralized facility at the Gorleben site, which is also the planned disposal site, for at least 50 years prior to disposal [1].

Germany has a policy to bring a geological repository into service by 2030 [5].

Hungary

Used fuel from its four Russian type of PWRs, known as Wodo-Wodyanai Energetichecki Reactors (WWER), producing 1.8 GWe is stored at the reactor sites at Paks in water pools. Hungary shipped its used fuel to Russia until as late as 1998 and is now self-managing its used fuel.

A centralized dry storage facility was licensed at Paks to store WWER reactor fuel in 1997 for an interim period. This facility was extended in 1999 to provide a total capacity of 378 tHM. Hungary is continuing to evaluate other dry storage concepts. It is expected that although the Paks facility has a design life of 50 years, used fuel may have to be stored for a period of about 100 years [14].

Hungary is planning to start direct disposal of its used fuel in 2047.

Japan

There are 51 LWR type reactors in Japan (45 GWe), four more are under construction (4.7 GWe) and 6 more are planned (7.2 GWe). Japan has relied on storage of its used fuel at the reactor sites in water pools. Roughly half of its used fuel has been sent to domestic and overseas plants for reprocessing.

Japan plans to convert some of its water pools at the reactor sites where they have excess capacities to common-use pools. These pools will serve two or more reactors to overcome capacity problems at some of the reactor pools. Two dry storage facilities using metal casks have been brought into service at Fukushima-Daiichi and Tokai-Daini plant sites with a total planned capacity of 44 metal casks.

Due to used fuel production exceeding reprocessing capabilities, Japan is planning the construction of centralized storage facilities in about 2010 for interim storage, possibly built and managed by the private sector [15].

Japan's Final Disposal Plan states that repository operations will start in about 2030.

Russian Federation

Russia has 30 reactors in operation (22.6 GWe), 15 LWRs, 14 Russian reactors known as Reaktor Bolshoy Moschnosti Kipyaschiy (RBMKs) and one FBR. Four more reactors (3 WWER and one RBMK) are under construction (4 GWe). Most used fuel is stored at the reactor sites in Russia.

Dry storage using metal and concrete casks is being put into service at two centralized storage sites at Leningrad nuclear plant site and the Kursk and Smolensk plant site. There is one centralized wet storage facility at the Krasnoyarsk reprocessing site. There are plans to develop a federal centralized dry storage facility with a capacity of 39,000 tHM by 2007 for Russia's RBMK and WWER fuel [1]. Reprocessed waste is planned to be centrally stored at its two proposed disposal sites ("Mayak" Enterprise and "Mining and

Chemical Combine"). At the Novaya Zemla Archipelago region, a near-surface central storage facility is being planned for used fuel that will not be reprocessed. This may be commissioned in the 2005-2010 timeframe [5].

Disposal is not expected to begin until 2025-2030.

Sweden

In Sweden, there are 11 PWR type reactors in operation and one PWR has been shut down with a total capacity of 1 GWe. Used fuel is stored at the water pools at the reactor sites only for a short period.

Used fuel is transported to a water-pool type centralized interim storage facility (known as CLAB facility) located underground. The Swedish used fuel management policy is to store its used fuel at the CLAB facility until firm decisions are made with regard to final disposal in a deep geological facility. It is expected that the CLAB facility may be operational until about 2050 at which time all the used fuel will be removed and sent to geological disposal.

The Swedish CLAB facility for centralized storage initially consisted of four water pools built in an underground cavern 30 m deep. The facility capacity is being extended with another rock cavern parallel to the first cavern.

Direct disposal is planned for all its used fuel starting 2015.

Switzerland

In Switzerland (5 LWRs in operation with 3.2 GWe capacity), reactor pools provide initial storage.

The Federal Council has approved the construction of a central interim storage facility for all its nuclear wastes including used fuel. The Wurenlingen Central Storage Facility has been built by the Swiss utilities-owned implementing organization, ZWILAG (Zwichenlager Wurenlingen AG). This facility provides additional capacity for used fuel in addition to its reactor pools. Both the high-level reprocessed wastes and the spent fuel assemblies will be stored in steel metal casks, which also serve as transportation casks. The casks will be stored in large storage halls provided with natural convection cooling [16].

The Swiss plans call for commencement of disposal around 2040/2050.

United Kingdom

United Kingdom has 16 Magnox reactors (i.e. reactors using magnesium alloy clad fuel), 14 Advanced Gas-cooled Reactors (AGRs) and one PWR in operation with 12.2 GWe capacity [17]. Ten reactors have so far been shut down (1.2 GWe). Used fuel is stored in pools at the reactor sites.

Used fuel is reprocessed and the reprocessing waste is stored at the reprocessing facilities at Sellafield. Used fuel from the Magnox and AGR reactors is initially stored at the reactor sites and then transported to a centralized interim storage at Sellafield where the used fuel is reprocessed. The British Sizewell B PWR is an exception where all the fuel is stored in water pools at the reactor site.

Britain has a dry storage facility at the Wylfa Power Station, which provides for the extended dry storage of Magnox fuel to overcome logistical problems in reprocessing. Longer-term storage of AGR fuel will be planned to meet the storage needs until a repository is available, for used fuel that is not reprocessed [1][18].

United Kingdom has no definitive plans for disposal.

United States of America

In the United States, used fuel, from its commercial LWRs (103 LWRs operating, 15 shut down and one being restarted, with a total operating capacity of 101 GWe) require interim storage until the deep geological repository being developed at Yucca Mountain is able to receive the fuel.

Utilities originally planned for only a limited amount of storage at the reactor sites expecting that the used fuel will be reprocessed or that the federal disposal repository would be operating much earlier. However, reprocessing was disallowed in 1977 on account of nuclear non-proliferation policy. Thirty-five U.S. plants have already run out of storage space at the reactor sites as of 2002. Only 11 nuclear plants have made arrangements at the reactor sites for storage for the full life of the reactors. Three of the 15 shutdown reactors have so far set up dry storage facilities for defueling reactor storage systems [19]. Faced with the problem of storage shortfall, the utilities adopted extensive design measures to increase storage space in the water pools by re-racking of used fuel.

GE at Morris, Illinois provided some centralized storage (both wet and dry) at the Morris, Illinois Facility. As the pools got filled, the utilities have put in place Independent Spent Fuel Storage Installations (ISFSIs) to increase their storage capacities until a geological repository is developed. Several dry storage designs are being used at the ISFSIs. Nineteen ISFSIs have been licensed as of 2001. Although ISFSIs are currently licensed for a 20-year storage, it is expected that storage for a longer period may be required [20].

Due to the delays in establishing a geological repository, it is expected that a centralized dry storage facility may also be required in addition to ISFSIs, possibly operated by the private sector. Initial attempts by the USDOE to develop a centralized storage called Monitored Retrievable Storage (MRS) have not been successful due to political and public acceptance factors [4].

The Yucca Mountain disposal facility is expected to become operational in 2010.

Table 1 provides a summary of the highlights of the twenty international programs that were reviewed. It should be noted that these programs provide for interim storage and should not be construed as long-term alternatives to disposal. It should also be noted that some countries have centralized facilities for circumstantial reasons rather than as planned national centralized storage systems (e.g. Canada).

Table 1. Summary of International Programs and their outlook

Country	Is centralized storage already available (A) and/or considered for the future (C)?	Current programs and outlook
Belgium	A, C	Centralized facilities have been commissioned at the Mol-Dessel site for vitrified high-level waste. Belgium may include in future centralized storage for its non-reprocessed used fuel.
Bulgaria	A, C	An AFR wet storage facility has been in operation since 1989 at the Kozloduy site, which provides centralized storage for six WWER type reactors. A dry storage facility is also planned [21].
Canada	A, C	Ontario Power Generation has put into operation two dry storage facilities at Pickering and Bruce sites in 1995 and 2002. Each storage facility provides centralized storage to two nuclear generating stations with four reactors at each station [8].
Czech Republic	C	A dry storage ISFSF facility at Dukovany was brought into operation in 1997 for four PWR reactors. A long-term interim dry storage system is also planned to provide centralized storage to four reactors at Dukavany and two reactors at Temelin [22].
Finland	C	Finland has a program for extended storage of its used fuel. It is not decided however whether the storage will be on-site or centralized [47].
France	A, C	The La Hague reprocessing facility provides for centralized storage prior to reprocessing. A centralized dry storage facility has been built at Cadarache (CASCAD facility) for used fuel that is not reprocessed [1].
Germany	A, C	Germany has licensed three centralized dry storage facilities at Ahaus, Gorleben and Greifswald. CASTOR V/19 casks are stored at these facilities. It is planned to further centralize all the used fuel in dry storage casks at the Gorlebin disposal site [1].
Hungary	A, C	A modular vault dry storage ISFS facility was placed in operation in 1997 to provide centralized storage for four WWER reactors. The facility is being expanded [14].
Japan	A, C	A centralized wet storage facility has been put into operation in Rokkasho Mura reprocessing facility. A dry cask storage facility started operation in 1995 at the Fukushima-Daiichi plant (Tokyo Electric Power Co.). Another dry storage is in operation since 2002 at the Tokai Daini plant (Japan Atomic Power Co.) These facilities together store three types of metal casks [15]. It is expected that another centralized storage facility with a capacity of 7700 tHM will have to be constructed.
Republic of Korea	C	A dry storage facility has been put into operation in 1992 at Wolsung to provide storage for CANDU fuel. AECL's Concrete Canisters are being used to store used fuel at this facility [1]. The revised plan (1998) calls for a centralized storage facility in 2016.
Lithuania	C	Lithuvania is considering long-term centralized storage as well as participation in regional projects with shipment of used fuel to other jurisdictions.
Netherlands	C	Netherlands is planning for centralized storage of its high-level waste. A dry storage system is under construction to receive high-level waste in 2004.
Russia	A, C	A centralized wet storage facility for RBMK reactors has been put into operation at the Krasnoyarsk reprocessing site (also known as

Country	Is centralized storage already available (A) and/or considered for the future (C)?	Current programs and outlook
		Mining and Chemical Combine). Two Metal Cask storage facilities are also brought recently into operation. A Centralized Storage facility to store used fuel from the RBMK and WWER reactors is planned at Krasnoyarsk for 2007 (33,000 tHM capacity). A collection pad for metal casks for used fuel from nuclear submarines is also planned [1].
Slovakia	C	A water pool facility is in operation at the Bohunice site providing centralized storage for four WWER type reactors. A new centralized storage facility/facilities is/are planned for all of Slovakia, which will include the four Bohunice reactors and four reactors at Mochovce [23].
Spain	C	A dual-purpose metal cask storage facility has been put into operation (2002) at the Trillo plant. A centralized storage facility is also under consideration [24].
Sweden	A	A centralized wet storage facility (CLAB) has been in operation since 1985 and is now being expanded for in-service in 2004.
Switzerland	A	A centralized storage facility is built for both high-level waste and un-reprocessed used fuel.
Ukraine	C	A dry storage facility at Zaporozhe is being built (Sevastyuk, 1995) [48].
United Kingdom	A	There are four large centralized pool facilities in Sellafield for storing used fuel from different reactor systems including overseas fuel prior to reprocessing. Used fuel from the first and the second-generation reactors (Magnox and AGR) and LWR fuel from overseas customers are stored in separate pools at Sellafield [1].
USA	A, C	A number of dry storage facilities at independent sites have been built. The reprocessing facilities operated by Nuclear Fuel Services at West Valley, New York and by GE at Morris, Illinois provided centralized storage in pool type facilities prior to reprocessing. In 1976 reprocessing was terminated. Since then, GE provided centralized wet and dry storage facilities at its Morris reprocessing facility site as commercial AFR storage. Some federal facilities have provided limited centralized storage such as the INEL facility, which has stored fuel from Shippingport and Peach Bottom Unit 1 plants. A nuclear utility consortium has been planning for a privately owned MRS for a number of years [4].

Future outlook

Although interim storage has been the responsibility of individual utilities in need of such storage in the past, the shift of responsibilities to implementing organizations charged with the task has resulted in many countries in a focus towards centralized and extended management of used fuel. Emerging national policies and organizational arrangements appear to have made this shift possible (e.g. Belgium, France, Spain and Sweden).

Many countries have initiated research and development (R&D) programs for extending the interim storage period. These programs are discussed later. With this R&D, there is an expectation in the technical community that the design life of the centralized storage facilities will increase from the current 20-50 years to a much-needed hundred years or more.

Dry storage technology is evolving rapidly and already it has become a mature international industry with a wide range of options and leasing of services. Competitive business attitudes are driving the industry and the technology is poised for accelerated growth.

The current trends to privatization and economic globalization are increasing market participation in the development of storage. There are leading international suppliers of storage technologies and services who have been participating in most storage programs and in many cases have provided innovative technologies required by the industry.

Lastly, we can expect increasing public input into decision-making with respect to new legislation, used fuel management policies, site selection and assessment of storage programs. An outstanding example of the public input on this issue was the public debate on the MRS facility in the U.S. [4]. In Canada, the federal government, following public participation in the Nuclear Fuel Waste Management and Disposal Concept hearing through the Canadian Environmental Assessment process, has directed the Canadian program to review long-term centralized and on-site storage options as alternatives to deep geological disposal [8]. Implementing organizations in several countries carry out similar reviews of future options and have public participation plans to seek public input into decision-making.

Technological Options

There are a number of technologies that are available for centralized storage of used fuel. In most respects, these are common to AFR storage as well. These are primarily water-cooled pools, and air-cooled metal casks, concrete casks, silos and vaults. Storage systems have been built with these technologies in a number of countries and a significant amount of experience has been developed [25][26]. There are also several technologies that are variations of the above that have been assessed but not yet commercially used. These consist of air-cooled drywells, in-ground casks, in-ground vaults and bunkers, and underground galleries [27][7].

While some of the earlier centralized systems were water pools, metal and concrete casks seem to be the currently preferred concepts by virtue of their long-term flexibility, modularity or ease of making additions, and passivity (i.e. independence from the need for active systems for the cooling and shielding of used fuel). Some of these designs are transportable as well and thereby limit direct handling of fuel to the initial loading phase.

Centralized storage systems could be built either above ground or underground and sited either at nuclear plant sites, at independent sites, or co-located with reprocessing or disposal facilities. In the short-term, implementing organizations have preferred above-ground systems located at nuclear plant sites. Where independent sites have been chosen, these sites have often been sites where there have been nuclear industry-related activities, such as nuclear research establishments. Some organizations have chosen to develop centralized storage in conjunction with management facilities for other radioactive wastes, such as low and intermediate level radioactive wastes (e.g. Swiss ZWILAG facility).

There are reputed suppliers who provide technologies as well as storage services. Some organizations have also developed the technological capability having carried out years of research and development, proof of concept studies and licensing (e.g., AECL and Ontario Power Generation). Due to the different types of nuclear fuel used in various reactor types, and the different ages of fuel considered for storage, the vendors generally provide a wide range of technology products and are flexible in meeting customized needs.

Broadly, the technologies can be categorized as wet and dry. In wet technologies, used fuel is stored in water pools, where water provides cooling for the used fuel and shields the environment from radiation. Water pools have been used at the reactor sites since the early days of nuclear power. In dry technologies, on the other hand, used fuel is stored in a dry air or inert gas environment. Cooling is provided by convection and shielding by the storage structures (metal, concrete etc). In developing storage systems, countries have used both wet and dry technology, underground and at-surface locations, and modular and fixed capacity approaches. Observers of the industry generally note that these demonstrate considerable achievement, technology maturation and flexibility [28].

Wet storage technology: water pools

Water pool storage is considered for centralized storage facilities because of the experience available with this technology and its flexibility to store fuels with high burn-ups. Used fuel is stored in open storage racks, modules or in sealed containers at the bottom of the pool. Pools are cooled with pumps and heat exchangers maintaining the water below 40° C. Cleanup systems are used to maintain good water quality. Used fuel is transported from the reactor sites in specially designed transportation containers, unloaded at the centralized storage facilities and stored in the water pools. The water pools can be located either above ground in earthquake-resistant buildings, or underground in caverns or vaults. An example of centralized storage using water pools is the underground CLAB storage facility in Sweden (Fig. 2).

In terms of centralized storage, the advantages of water pool storage are that it keeps all future options open, storage temperatures are considerably lower than the temperature ranges encountered in dry storage, and it provides a large margin for future reactor fuels which are expected to have higher enrichment and enhanced discharge burn-up (i.e. increased heat generation and radioactivity as a result), including mixed-oxide fuel (MOX fuel) and other advanced fuels [29]. Water pool storage is also convenient in assuring safeguards and for carrying out fuel inspection during storage. On the negative side, however, water pools are known to impose a greater institutional burden in terms of care taking and maintenance and perhaps somewhat greater risk in terms of potential loss of cooling scenarios.

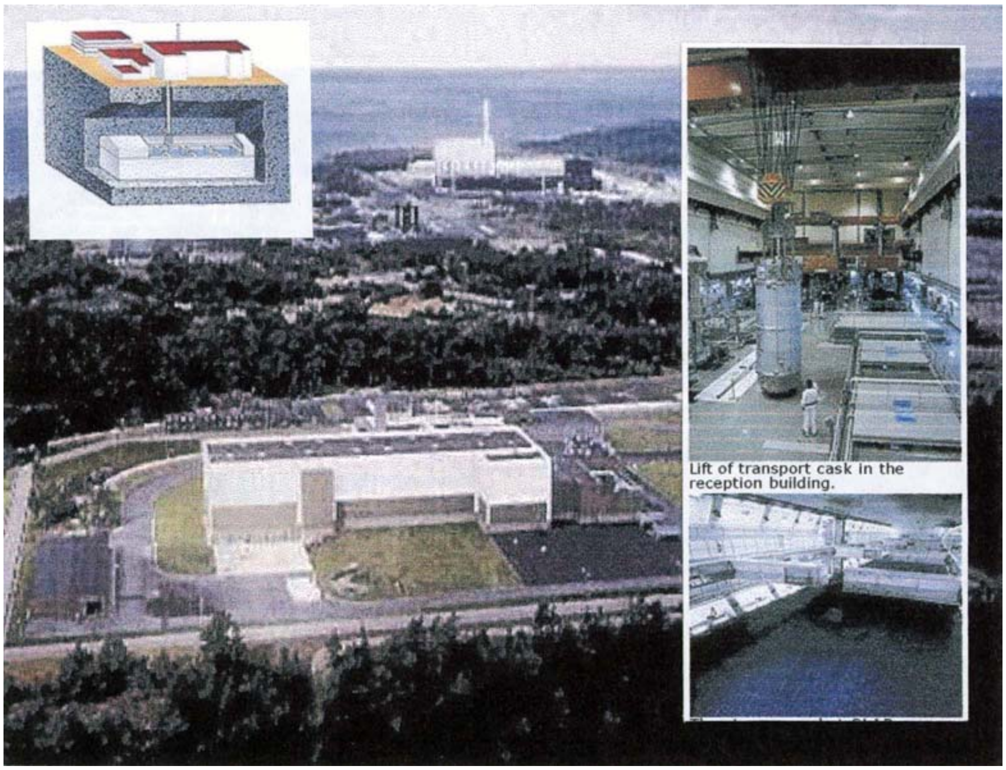


Figure 2: Sweden's centralized water pool storage facility CLAB [6]

CLAB provides for centralized interim storage in water pools in rock caverns 25 m below the ground. The facility is being expanded to store about 8000 tonnes of used fuel from the Swedish nuclear program. The facility will also include a special encapsulation plant for conditioning used fuel for disposal, construction of which will start in 2005.

CLAB data:

Owner:	SKB (Svensk Karnbranslehantering AB), a utilities-owned company
Location:	Oskarshamn, near the Oskarshamn nuclear plant (OKG)
Start of construction:	1980
Start of operation:	1985
Current storage capacity:	5000 tonnes of uranium (20,000 BWR fuel and 2500 PWR fuel)
Processing rate:	300 tonnes/year
Number of employees:	100 full-time staff
Number of pools (current):	4 plus one reserve
Pool temperature:	36° C
Cooling capacity:	8.5 MW
Operation and Maintenance:	By OKG Aktiebolag
Construction cost:	Approx. SEK 1,700 million (350 million Canadian dollars approx.)
Operation cost:	Approx. SEK 100 million/year (approx. 20 million Can$)

Dry storage technology

Used fuel can be stored in dry facilities after a few years of initial cooling in the water pool. Dry storage facilities are an attractive alternative to water pools as most of these facilities are naturally cooled and require less operational effort. Dry storage of spent fuel is being particularly recognized as a more flexible option than water pools in terms of capacity building. The key technologies are: concrete casks, metal casks, silos or bunkers, and vaults.

Concrete casks

A concrete cask is basically a concrete container with an inner cavity. Used fuel is loaded into this cavity and the container sealed after loading. The concrete provides shielding, and a metal liner in the cavity provides containment. Casks are either cooled by natural convection or ventilated and can be stored either horizontally or vertically. Often these casks are stored inside a building to protect them against the weather. Concrete casks are generally large, several metres in size. Ontario Power Generation (OPG)'s Dry Storage Container (DSC) is an example of a concrete cask. The DSCs are naturally cooled, and are stored in warehouse-type buildings at the OPG's Pickering and Bruce Waste Management Facilities [9][10].

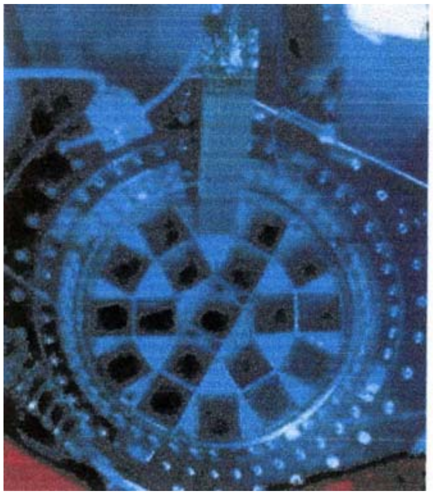
Metal casks

The metal casks are the most mature of all cask designs. Metal casks are similar to concrete casks except that metal such as steel replaces concrete as the structural material for the cask (Fig. 3). A typical metal cask is about 5 m long and 2-3 m in diameter and weighs about 100 tonnes when loaded with used fuel. Each metal cask can hold about 20-30 PWR fuel assemblies or 45-70 BWR fuel assemblies [4]. The fuel assemblies are stored inside the cask in baskets made of neutron-absorbing materials such as borated stainless steel to eliminate criticality hazards with LWR fuel for which they are designed. The cask is made of forged steel, cast iron, or stainless steel of suitable thickness to provide shielding. The outside surface is sometimes finned to enhance cooling. The casks are stored in the open on a concrete pad or warehouse-type buildings.

Heat removal is by conduction through the structural material. The metal casks are sealed usually with two lids to assure containment of radioactivity. Several designs of these metal casks are marketed, such as Transnucleaire/GOGEMA Logistics (ACL) TN casks, GNB's CASTOR casks, Westinghouse's MC casks, and Nuclear Assurance Corporation's NAC casks.

Silos or bunkers

Silos or bunkers are large monolithic concrete structures, similar to concrete casks but much larger in size. These are generally not transportable and are anchored to the ground. Atomic Energy of Canada's Concrete Canisters, Nuclear Horizontal Modular Storage (NUHOMS) silos in the USA and Nuclear Assurance Corporation's Vertical Concrete Casks (VCCs) fall into this category (Fig. 4). AECL Concrete Canisters, for example, are 6.5 m high and 3.1 m in diameter and contain 540 CANDU fuel bundles in one of its designs. The fuel bundles are loaded into stainless steel baskets, which are then seal-welded. These baskets are then emplaced in the canister of the concrete silos.



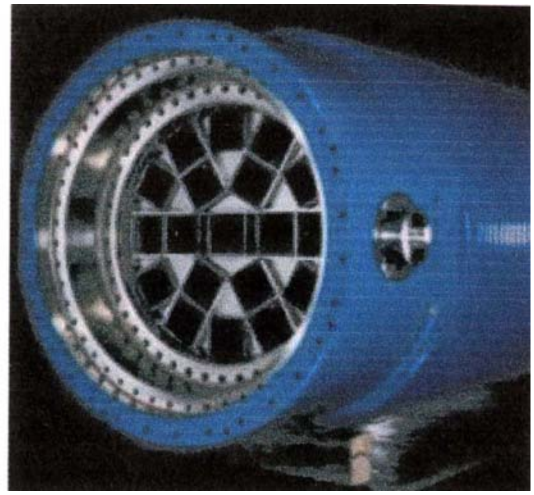


Figure 3: Example of a metal cask [32]

This is a CASTOR V/19 metal cask used at the German Ahaus centralized storage site. The storage facility although built in late 1980's was not commissioned until 1992 as plans for earlier commissioning was halted by a court order. The original design capacity was 420 storage casks. In 1992 this was extended to include 320 CASTOR casks. Between 1992 and 1995, the facility received 305 CASTOR casks containing used fuel from the decommissioned Thorium High-Temperature Reactor (THTR 300). Expansion of the facility has been licensed to receive reprocessing waste from German reactors and low and intermediate waste from reactor operations.

Vaults

Vaults consist of concrete structures containing an array of cells for storing used fuel. Each storage cell consists of metal storage tubes or storage cylinders. Used fuel is loaded into these tubes with fuel handling machines in a charge hall at the facility or off-site at the reactor pools. These are generally located above the ground level and the heat is generally transferred to the atmosphere by natural convection. The vaults can also be below ground. Magnox dry storage at Wylfa in the UK and the MVDS facility in Paks in Hungary are examples of vaults where used fuel is loaded at the facilities. CANSTOR at the Gentilly-2 plant in Canada, CASCAD facility in France, and the Fort St. Vrain Modular Vault Dry Storage (MVDS) facility in the USA (Fig. 5) consist of designs where the fuel is pre-loaded into containers, which are then sent to the vault.

Other concepts

Besides the concepts discussed earlier, there are a few other concepts that have been studied and are considered conceptually feasible. These consist of drywells and in-ground casks. In the drywell concept, used fuel in dry sealed containers is stored in ground. An on-site transporter with a shielded transfer cask is used to transport and load the containers to a designated drywell. A centralized storage facility with an array of drywells was proposed for the Monitored Retrievable Storage (MRS) facility in the US. Used fuel can also be stored in a drywell facility located in underground tunnels in a manner similar to that in a geological disposal concept. Concepts in which casks are stored in drywells have also been studied [27]. Underground concrete bunkers and storage galleries are being reviewed in the French program [7].

Figure 4: Example of a concrete silo [33]

These are the vertical concrete casks (VCCs) manufactured by NAC International and constructed in-situ at the Maine Yankee Atomic Power Station by construction contractor Power Maintenance Resources Inc (PMRI). The facility is an ISFSI. The pictures show the in-situ concrete silo (above left), concrete pads for housing the silos (right) and the concrete liner for storing the used fuel (bottom).

There are a large number of designs available from vendors on the international market, particularly for metal and concrete casks. In the U.S., a number of these designs are pre-approved for use with a general license. Various countries are bringing into service storage facilities using these designs.

Figure 5: Example of a vault concept: Fort St. Vrain Facility in the US [34].

Fort St. Vrain is an USDOE owned ISFSI at Platteville, Colorado. It holds 130 cubic metres of used fuel from the now-decommissioned Fort St. Vrain commercial demonstration power plant. The Idaho National Engineering and Environmental Laboratory operate it for the USDOE.

Facility data:

Facility:	143 feet long, 73 feet wide and 80 feet tall heavily reinforced concrete building
Constructed in:	1991
Facility life:	40 years until fuel removal in 2027
Design features:	Withstands wind speeds of 360 mph; flooding up to six feet and 0.1 g earthquakes
Cooling:	Natural convection of air
Capacity:	244 steel fuel tubes double sealed with metal O-rings and bolted lids.

Multi-purpose containers (i.e. single containers for storage, transportation and disposal) are also being studied in some countries, but are not yet commercially available [30][31]. This recent development uses a universal container system consisting of an inner metal container (called multi-purpose container), which uses special over-packs for storage, transportation and disposal of used fuel. The POLLUX cask in Germany is designed to meet multi-purpose container requirements for storage, transport and disposal in a salt repository and a demonstration facility for packaging LWR fuel in POLLUX casks has been built [1].

Besides the storage systems discussed above, centralized storage also requires various infrastructure and services. These include an off-site transportation system, fuel dispatch stations at the various reactor sites feeding into the centralized storage system, systems for container or cask reception, hot cells with automatic welding systems for sealing containers, administrative/technical buildings, security and safeguards systems, and systems for radiological monitoring and radioactive waste management. The storage industry caters to most of these infrastructure needs and services.

Specific considerations in centralized storage

The centralized storage option, as currently practiced in most cases, is an intermediate option between short-term reactor site storage and a future long-term management option to be decided on once a national strategy for the long-term management of the used fuel has been developed. Generally, the long-term option selected in many countries has been deep geological disposal. However with the delays and setbacks, and lack of public support for disposal options, many countries are enhancing their programs in terms of alternatives, particularly through consideration of extended storage [5]. The timeframe of storage is evolving from the 30-50 years initially considered for interim storage to 50-100 years.

On the one hand, centralized storage requires a staged approach allowing for capacity extension to meet used fuel quantities from various reactors requiring storage; on the other hand it has to be compatible with future needs such as in terms of fuel handling. There may be instances where the timelines for disposal have not been clearly established, or where a long wait period is anticipated such as in developing new technologies (e.g. P&T). The centralized storage option needs to forecast and take into account the long-term flexibility and the compatibility required for the future handling of the used fuel.

Extending the storage period has been a general trend in many countries irrespective of decisions regarding disposal. Timeframes of 50-300 years are being considered. The ability to retrieve used fuel cannot be compromised during extended storage in order to allow future reuse or treatment of fuel. Potential degradation of used fuel during extended storage due to a number of reasons such as time, temperature, radiation and other environmental conditions needs to be taken into account.

Where the service life of the current storage is inadequate in meeting the required storage period, there may be a future need to transfer used fuel from one set of facilities to another. This again is a considerable challenge in terms of used fuel handling during the centralized storage period.

The centralized storage systems need to be interfaced with at-reactor storage and AFR storage facilities, which may involve specialized fuel handling (e.g. cranes, loading cells, decontamination facilities, transfer corridors and terminals etc.), and transportation systems (e.g. licensed transportation containers, vehicles for road, rail or water transportation, and routes).

Institutional frameworks

The nuclear waste owners generally take responsibility to ensure that storage systems are available for used fuel. Often they are also the ultimate customers and operators of used fuel storage systems. However, due to the increasing inventories of used fuel and the long-term management required, national governments have been increasingly getting involved not only in rule-making with respect to used fuel management, but also in the management of the used fuel for the long term. Centralized storage is no exception to these emerging organizational developments.

Governments take responsibility for setting up the legislative framework and making political decisions for the implementation of the national policies for the long-term management of used fuel [35]. Dedicated implementing organizations have been set up with a legislative basis in many countries to provide direction to the long-term management of used fuel including centralized storage (Table 2).

The managing institutions generally fall into three types: government-administered organizations, government-owned companies and the private sector [5]. Consortia involving nuclear plant owners, governments and the private sector are also possible.

In the case of government organizations (either government administered or owned), these organizations may take direct control of the programs taking title to the used fuel. These organizations then implement the storage systems with tendering arrangements with the industry. Such institutional frameworks are often perceived to be the most accountable in terms of public trust, transparency and financial accountability. Germany, USA, Belgium, Czech Republic, France, Hungary and the Russian Federation are examples of Government organizations managing used fuel [5].

The entry of the private sector in providing institutions for the management of used fuel is a new trend. For example, the Japanese law for regulation of nuclear power reactor and other nuclear operations (The Regulation Law) amended in 1999 has opened up in Japan new business ventures in the private sector. The law allows the private sector to become full service providers, while the government provides the regulatory role only. The Japanese government is expected to license a private organization to construct and operate a centralized storage facility [15]. Finland, Japan, Netherlands, Slovakia, Spain, Sweden and Switzerland have private organizations (mostly utility-owned) managing used fuel [5]. The Canadian NWMO is a local example of Canadian utilities (public and possibly public/private in future) managing used fuel.

There have been discussions in various forums on taking up a multi-national approach to storage based on voluntary co-operation among the countries. Although this approach can help smaller countries that may not have the means to provide effective long-term management, it is argued by some that such plans could have a negative influence on the programs of countries that wish to offer such facilities. Whether the forces of globalization and economics will offset such views is not yet clear.

Table 2. Implementing organizations in various countries.

Country	Implementing Organization	Type of Organization/Sector
Belgium	ONDRAF	Government-owned
Canada	NWMO	Public and private utilities
Finland	POSIVA	Private
France	ANDRA	Government-owned
Germany	BfS	Government-administered
Italy	NUCLECO	Semi-public
Japan	NUMO	Private
Netherlands	COVRA	Private
Spain	ENRESA	Private
Sweden	SKB	Private
United States	OCRWM	Government-administered

Activities associated with centralized storage consist of long time frames involving a number of decades as a minimum. These activities are neither simple nor inexpensive and require institutional control with necessary investment of financial and human resources. The organizations collect financial resources needed for future activities while the nuclear plants are still in operation. The financial resources consist of funds or reserves collected as a levy on electricity rates or as a contribution from the nuclear waste owner and maintained by organizations independent from nuclear plant owners.

It is also necessary that centralized storage systems, in view of their potentially long lifetimes, include appropriate features that address security and safeguards issues such as proliferation and terrorism by limiting possibilities through which such acts could be carried out. World bodies such as the IAEA emphasize intrinsic technological features as well as extrinsic institutional arrangements for control and verification of the used fuel inventory at these facilities [36]. It is important to take the requirements into account during the design phase.

Current developments

Current technologies used for centralized storage are an extension of AFR storage technologies and are primarily focused on the short term, of say 20-50 years. Extension of these technologies for up to 100 years is generally believed to be possible. Many countries, including Canada, have research and development programs to ensure such extension of the storage period. However for longer terms, such as a century or more, a number of questions need to be answered related to, among other things, the integrity of the used fuel, durability of structures and monitoring techniques, institutional stability and continuity.

The fuel cladding (i.e. metal tubes containing fuel in a used fuel assembly) usually provides a barrier for radioactivity during storage. The integrity of this cladding is an important consideration in the long-term storage and is of concern irrespective of the type of fuel or the type of storage. Many countries, including Canada, have put in place research programs to investigate used fuel integrity in the long term in wet and dry environments. Such programs generally track any degradation of fuel or the cladding by periodic destructive examinations of stored fuel and alert used fuel managers on findings relevant to long-term used fuel integrity in storage [37].

Conditioning of used fuel is part of the strategy for disposal. The purpose of conditioning is to immobilize used fuel during disposal. Technically, conditioning involves the packaging of used fuel inside specially designed containers that are made of durable materials such as copper or stainless steel. This includes backfilling the packages with immobilizing materials such that the container can better withstand external pressure in a sealed underground disposal environment. Conditioning makes retrieval of individual fuel assemblies somewhat difficult. Where retrieval of individual used fuel assemblies is not a key consideration (e.g. where disposal is decidedly the final step), the option of conditioning prior to long-term storage is considered in enhancing the safety of long-term storage [7]. Conditioning technology is generally well researched and prototype facilities have been developed (e.g. Germany and Sweden); however, large-scale conditioning facilities have not yet been built.

Many countries have established programs on long-term storage and are closely monitoring these programs in support of their long-term storage options. Advanced concepts suitable for long-term storage are also being researched. It is also important to maintain a continuity of knowledge and information on stored fuel using durable information media (i.e. media that can be read and used for more than a hundred years). As new generations of nuclear fuel are developed (e.g. higher burn-up fuels and MOX fuels), further research would be needed to gain an understanding of the long-term integrity of these fuels.

Table 3 provides a list of international programs related to long-term storage aspects.

Table 3. Long Term Storage Programs in Various Countries

Country	Long term storage programs
Canada	Storage parameters being monitored for Dry Storage Containers (DSCs); conceptual studies of centralized long-term storage are being carried out. Extensive fuel integrity research work was carried out by AECL in support of storage and disposal programs [1][10].
France	Five concepts including wet and dry storage are being studied in the context of very long-term storage (300 years), as part of the third axis of the 1991 French Law to investigate long-term storage of radioactive wastes prior to disposal [1][7].
Germany	Studies and prototype facilities for the conditioning of used fuel for extended storage and disposal are being carried out [1][5].
Japan	An advisory committee of the Ministry of Economy is studying a centralized AFR storage facility. Japan has a number of programs to determine the long-term integrity of used fuel in wet and dry storage conditions [1].
Russia	Russians are carrying out research to determine the maximum storage times for dry stored fuel. They are also developing dual-purpose metal and concrete casks. In 2001, the President approved a package of laws to resolve nuclear fuel cycle problems including extended storage of used fuel [1][5].
Sweden	Sweden is developing an encapsulation plant at its CLAB facility for containerization of fuel for long-term storage and disposal [1].
USA	USA has a multi-year program to examine fuel and cask components to provide confirmatory data to establish suitability of dry storage for storage period beyond the currently licensed 20 years. USA has also comprehensive programs on used fuel packaging including development of universal container systems for storage, transportation and disposal [1][30].

RELATED AREAS

There are various related areas of interest to centralized storage such as development of technical requirements, site selection processes, regulatory and environmental requirements, resource requirements, operation and maintenance, infrastructure needs, public acceptance, and project implementation. These are briefly reviewed below.

Technical Requirements

The technical requirements for centralized storage times of up to 30-50 years have evolved in many countries from the at-reactor storage technology for wet storage and from the development activities for dry storage. The presently anticipated time frames for storage are generally now approaching about 100 years. In this timeframe, the technological issues of centralized storage are generally believed to be either resolved or resolvable, as evidenced by the commitment of a significant number of centralized storage facilities in the world, using both wet and dry technologies for such time frames.

The research and development of the generic storage technology in terms of used fuel performance, storage conditions (e.g. water chemistry in wet storage, allowable fuel temperatures in dry storage etc.), and structural limits (pool liners, concrete etc.) have been of use in the development of centralized storage facilities. There is a significant amount of information available in this regard based on several decades of research and 50 years of storage experience worldwide [1][25][26].

For longer-term storage, such as for 50-300 years, the additional technical requirements, are still in the research and development stage. These relate to fuel integrity, structural durability, handling of used fuel after long-term storage, encapsulation and packaging of the used fuel for disposal, and monitoring technologies and techniques [1].

In cases where long-term plans have not been put in place it will be necessary to foresee future requirements at the time the centralized storage is designed. These would include necessary institutional measures for continued monitoring and remediation, and eventual used fuel retrieval and facility decommissioning. Where ultimate solutions may entail a very long wait period (several hundred years), there may also be a need to manage used fuel in successive facilities and to have necessary design features to cope with such a situation.

Site Selection

The site selection processes for centralized storage depend on the availability of existing sites (such as nuclear plant sites) and independent or "green field" sites. In either case, site selection usually involves a range of stakeholders, particularly, the governments and the local communities. Traditional approaches used in the past, which relied largely on technical and scientific criteria, are now yielding to co-operative approaches, where new sites are sought in cooperation with host communities.

The questions that often arise in the site selection for centralized storage relate to the storage times and the guarantees that the used fuel will one day be removed and transferred from the site. In countries where disposal policies have lagged, these issues take a prominent role in public debate and community consultations [38]. Despite these issues, the implementing organizations have generally been able to succeed in obtaining public acceptance for storage as seen in the recent successes such as Switzerland's ZWILAG facility, Netherlands' engineered high-level waste storage facility (HABOG facility) and the Canadian Bruce Waste Management Facility (Bruce WMF).

Regulatory and Environmental Requirements

Requirements for regulatory licensing and environmental approvals differ from country to country. Technologies that have been licensed in the country of origin usually fare better in terms of regulatory acceptance. As a matter of interest, the USNRC publishes a list of NRC-approved casks in the U.S. [39]. Existence of operating prototypes and demonstration facilities also has a strong bearing on the regulatory acceptance of technologies. Processes related to environmental assessment (also called environmental impact statement or EIS) provide a venue for interfacing with various levels of governments and the general public through the public consultation and hearing process. Implementing organizations generally strive to obtain public input through public participation programs.

Resource Requirements

Most implementing organizations do not have in-house resources for implementation of storage systems and rely on Architect-Engineers and project management organizations. Mostly private sector vendors have carried out the development of the technical concepts, although there are exceptions (e.g. Canada, where AECL and OPG have shared the research and development of dry storage). The private sector involvement has been steadily growing with economic globalization. Many multi-national vendors now offer full service ('pool to pad' service) support in implementing storage.

The costs of long-term used fuel management are borne by the producers of used fuel. There are a number of financing schemes set up in different countries for internalizing the costs into power production. While in some countries, a fee is levied on the electricity and is collected in segregated funds, in some other countries, these costs are shown as liabilities on the balance sheet [40].

Operation and Maintenance (O&M)

In terms of centralized storage, the O&M criteria focus on simplicity, passive features to minimize O&M, and a longer-term view in reducing O&M costs and training. The preference for the dry storage cask over other storage types primarily relates to the favorable O&M characteristics of these casks.

Infrastructure

Availability of infrastructure is a key consideration. This includes transportation systems, local site infrastructures, and the infrastructures at the nuclear plant sites to arrange for off-site shipment of used fuel. While some dry storage casks are licensed as transportation containers as well, transportation of used fuel in licensed IAEA-designated Type B containers (metal containers) is still the reference approach used in many countries. Development of the transportation infrastructure includes selection of modes (rail, road or water), containers and vehicles, and emergency response systems for managing transportation mishaps. Transportation program is a considerable investment in a centralized storage program, particularly where the facility is located hundreds of kilometers away.

Public Acceptance

The used fuel storage, to be fully centralized, requires a regional or national approach to storage. The decision to implement such a plan is mainly political, since the owners of used fuel cannot implement such plans without public consensus. As potential hosts for a centralized storage, communities at these facilities are the hosts of the facilities for used fuel from various reactors in the region or the nation and become involved in the decision-making processes. Obtaining co-operation from communities in the site selection and public and political acceptance therefore become important objectives. The failure of the USDOE program to obtain such acceptance resulted in the deferral of the Monitored Retrievable Storage (MRS) in the U.S. in the 1980's [4].

Public input into decision-making has steadily increased in many countries, spanning all areas, such as legislation and policies, site selection, technology selection and overall participation in the project. Transportation of used fuel has always raised public concern in many countries. Countries have adopted cooperative approaches with communities involved in the selection of new sites and transportation routes.

Communities have generally tolerated storage at the nuclear plant sites under the assumption that such storage will be temporary and will be eventually removed from the sites. The public dialogue of used fuel storage at the Bruce WMF during its Environmental Assessment provides some evidence of this observation. The Bruce WMF is sized to provide for the storage of all used fuel from Bruce reactors over their operating lives.

Project Implementation

It is not often clear how to choose the best option with respect to centralized storage systems. Recommendations suitable to one country are not necessarily the best for another country due to circumstances specific to each country. Furthermore, the circumstances change from time to time as used fuel management strategies change and technological advancements take place.

The implementing organizations generally include independent reviews in their programs, which may include reviews of systems analysis, feasibility studies, market evaluations and regulatory and environmental evaluations. Trends towards global tenders and bid competition are common to many countries embarking on centralized storage.

Given the availability of mature technologies and eager suppliers, centralized storage systems could be put in place in about 5-10 years, of which the initial few years are taken to carry out the necessary feasibility studies, and obtain environmental and site approvals. The loading phase (i.e. period during which used fuel is placed in storage) is generally longer than the initial construction phase, constrained by the logistics of transportation, and used fuel throughput from preceding facilities.

However, future systems for long-term storage (storage for 100 years or more) may necessarily take longer due to the additional issues related to the longer term.

ANNEX: THE CANADIAN PROGRAM

Centralized storage options have been studied in Canada since the 1970's [41]. In the mid-seventies, an expert committee consisting of members of Ontario Hydro (now Ontario Power Generation) and Atomic Energy of Canada Limited known as the Committee Assessing Fuel Storage (CAFS) reviewed a number of conceptual alternatives for centralized storage, which included water pools, concrete canisters and dry vaults. These options were further developed in the late seventies and the results were reported extensively at the time.

Under a request from the Ontario Government, Ontario Hydro assessed the siting options for the storage of used fuel in 1979 based on the optimistic generation growth scenarios at the time. Two major options, on-site storage and centralized storage (for all of Ontario Hydro) were reviewed. The choices for a site for centralized storage, namely storage at the disposal facility site and storage at an independent site, were also reviewed. The study recommended that Ontario Hydro should follow the on-site storage strategy until decisions are made for reprocessing or disposal. The study concluded that adequate space is available at the plant sites until at least 2025 based on additional water pools as the storage method [42].

Extended storage of used fuel for several hundred years was reviewed by another study in the early 1980's [43]. The study reviewed nine extended storage concepts consisting of water pools; concrete containers and dry vaults, each located either at the ground surface, in near-surface caverns or deep underground. The study concluded that dry storage in concrete containers located above ground is the most flexible option to follow for extended storage development [44].

These studies led to the development of the dry storage containers (Fig. 6) in Ontario Hydro as a flexible option for additional storage [45]. Dry storage containers are currently used at the Pickering and Bruce WMFs and are planned at the Darlington WMF [10]. At Pickering WMF, The Phase 1 Facility came into service in 1995 and has a capacity of 700 DSCs. Phase 2 of the project will come into service in 2007 with an additional capacity of 800 DSCs [9]. The Facility will accommodate all the used fuel from the Pickering reactors and hold them in storage until long term plans are made for used fuel management in Canada. A facility for storage of all fuel from Bruce reactors has been put into service in 2002, and another one is planned for the four reactors in Darlington. The DSCs have a design life of 50 years, but it is expected that with ongoing maintenance and inspection, they would be suitable for storage for a much longer period [10].

In parallel with developments in Ontario Hydro, AECL has developed two concepts for dry storage of used CANDU fuel: the modular vault concept known as CANSTOR (Fig. 7) and the concrete canisters (Fig. 8). These concepts are in use at Quebec Hydro and New Brunswick Electric Power Corporation respectively for on-site storage. AECL is also managing used fuel from its early reactors (NRX and NRU reactors) at a centralized facility at the Chalk River Laboratories, and from Douglas Point nuclear plant in a dry storage facility at the plant site.

Figure 6: OPG Dry Storage Containers [46]

The Dry Storage Container is a steel lined concrete container, 63 tons in weight, and with a capacity for four modules of 96 CANDU fuel bundles each. The containers are loaded with used fuel inside the pools and then drained, decontaminated and vacuum dried. It is then transported to the dry storage facility in a transporter. It is then filled with helium gas, and seal-welded. The container is then placed in storage. Due to lower burn-up (compared to LWR fuel) and absence of criticality hazards with CANDU fuel, these containers are somewhat simpler to design than metal casks or concrete casks for LWR fuel.

Studies were carried out in the Atomic Energy of Canada laboratories to determine the structural integrity of used fuel during storage. Canada also participated in the international program on the integrity of used fuel in wet and dry storage known as BEFAST programs (Behaviour of Fuel Assemblies in Storage, 1981 to 1996). These programs led to indications that used CANDU fuel should maintain its integrity in wet and dry environments for 100 years. If the fuel is defective however, this period could be reduced to 50 years. Canada is now participating in the first phase of the IAEA Spent Fuel Performance Assessment and Research (SPAR) program which is focused on various long-term storage issues related to used fuel and their effect on storage and disposal [1]. Unless further research extends these limits, long-term storage would necessarily need more attention in terms of storage safety such that release of radioactivity from the fuel does not become a problem in long-term storage.

Figure 7: CANSTOR Facility at the Gentilly-2 site [46]

Figure 8: AECL Concrete Containers at Point Lepreau [46]

Ontario Power Generation has plans for a long-term monitoring program of four Dry Storage Containers including the study of long-term evolution of used fuel in these containers at its Pickering WMF.

The Federal Environmental Assessment and Review Process on the Canadian Nuclear Fuel Waste Management and Disposal Concept reviewed the Canadian Program for the long-term management of used fuel, which focused on deep geologic disposal of used fuel in the Canadian Shield. In its Panel Report, it recommended, among others, that various long-term options should be compared [8].

The Canadian utilities and AECL, through the NWMO (as noted in page 10), are currently reviewing these long-term options. Reactor site long-term storage, centralized long-term storage, and deep geological disposal are being further developed to a stage where they can be reasonably compared.

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GLOSSARY

AFR storage: Storage of used fuel in away-from-reactor storage facilities.

Casks: Containers for used fuel, which provide both containment and shielding against radiation.

Centralized storage: Storage of used fuel at a site that receives used fuel from a number of reactors thus providing a central facility for storage.

Conditioning: Method of immobilizing used fuel for disposal. It is generally done by the use of long-lasting containers. Used fuel is packaged in these containers, backfilled and sealed.

Disposal: Emplacement of used fuel in an engineered deep geological facility (also called repository) without the intention of retrieval.

High-level wastes: Wastes that are removed from used fuel during reprocessing. These are highly radioactive and are generally vitrified before storage.

Interim storage: Storage in the interim period, i.e. until solutions are available for the long-term management of used fuel (e.g. disposal).

Long term: Generally used to imply period beyond the current storage of 20-50 years.

Magnox: A type of gas-cooled reactor in the United Kingdom using fuel with magnesium alloy cladding.

On-site storage: Storage of used fuel at the reactor sites.

Partitioning and transmutation: Removal of waste isotopes from the used fuel during reprocessing with the objective of separating these isotopes (partitioning) and eliminating their radioactivity by changing them to non-radioactive isotopes (transmutation). In transmutation, the isotope target material is bombarded with nuclear particles in an accelerator or a special-purpose reactor.

Reprocessing: Chemical processing of the used fuel to remove plutonium and uranium for reuse as recycled fuel in reactors.

Used fuel: Nuclear fuel that has been removed from a nuclear reactor following its irradiation for energy production. Used fuel is hot and highly radioactive at the time of removal and must be carefully managed.

Vaults: Engineered facilities for storing used fuel in a dry environment.

Water pools: Swimming pool type water pools used for storing used fuel

ACRONYMS

AECL: Atomic Energy of Canada Limited
AFR: Away-from-reactor
AGR: Advanced gas-cooled reactor
BWR: Boiling water reactor
CANDU: Canadian deuterium uranium reactor
CANSTOR: AECL modular dry storage design for CANDU fuel
CFR: Code of Federal Regulations, U.S.
CLAB: Swedish water-pool type underground centralized storage facility
DOE: The U.S. Department of Energy
DSC: Dry Storage Container (OPG design)
FBR: Fast breeder reactor
GCR: Gas-cooled reactor
GE: General Electric
GWe: Gigawatt electrical (1 GWe is a billion watts of electrical power)
IAEA: International Atomic Energy Agency
ISFSI: Independent spent fuel storage installation
LWR: Light water reactor (could be both PWR or BWR)
MACSTOR: AECL dry storage design for LWR fuel
MOX: mixed-oxide fuel
MRS: Monitored retrievable storage
MVDS: Modular vault dry storage
NFWA: Nuclear Fuel Waste Act (2002) in Canada
NRC: Nuclear Regulatory Commission (US)
NUHOMS: Nuclear horizontal modular storage system
NWMO: Nuclear Waste Management Organization (in Canada)
OPG: Ontario Power Generation
P&T: Partitioning and transmutation
PWR: Pressurized water reactor
RBMK: Russian design of a water-cooled graphite-moderated reactor
ROK: Republic of Korea
SKB: Swedish Nuclear Fuel and Waste Management Company
tHM: metric tons (or Mg) of heavy metal (i.e. uranium or plutonium)
THTR: Thorium high temperature reactor.
VCC: Vertical Concrete Cask
WMF: Waste Management Facility (OPG)
WWER: Russian design of a PWR
ZWILAG: Swiss organization, Zwichenlager Wurenlingen AG