Single Storage Canister to MACSTOR® - 14578

Canadian Solution and Experience in Responsible Spent Fuel Management

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ABSTRACT

Candu Energy is a wholly owned subsidiary of SNC Lavalin. As former commercial division of Atomic Energy of Canada Limited (AECL), Candu Energy now holds exclusive rights to all aspects of CANDU® technology. The company has the experience in spent fuel storage technology spanning four decades. In this capacity, Candu Energy is a valued contributor to the development and implementation of dry spent fuel management facilities in Canada and internationally. CANDU® spent fuel storage systems are well proven and benefit CANDU® reactor operators with many years of successful safe operating experience.

In early 60's, AECL Chalk River Laboratories recognized need for dry storage application. The research was initiated at AECL Whiteshell Research Laboratories. The first concrete canisters were developed and built in 1976 at the same site. Its development continued through several canister projects at the Douglas Point power plant, Nuclear Power Demonstrator (NPD), Point Lepreau Nuclear Power station, Wolsong 1 Nuclear Power station, eventually evolving to the first MACSTOR® 200 at Gentilly-2 followed by MACSTOR® 400 at Wolsong 2-3-4, Korea and Qinshan 1-2, China. The total storage capacity of the first canisters was 1.83 MgU/canister. The total storage capacity of the latest MACSTOR/KN-400 is 456 MgU of spent fuel/unit. During the period of about 50 years, the capacity of storage structures has been increased by a factor of almost 250, from the initial design to the most recent storage. With inherent safeguard features like double containment, internal atmosphere monitoring capability and the IAEA safeguards, MACSTOR® is one of safest storages at the industry marketplace. Flexibility of design enables MACSTOR® concept to be adapted for storage of non-CANDU fuel types as well.

The spent fuel storage costs are largely determined by heat load in an intermediate dry storage facility. The lower burnup of CANDU® fuel translates to the lower heat load during storage. This is the main feature that keep costs of CANDU® "back-end" comparable to Light Water Reactor (LWR) spent fuel dry storage costs, despite a higher volume of spent-fuel production with CANDU®. Additional cost benefits results from small size and simplicity of CANDU® fuel bundle which utilizes natural uranium. These factors directly reduce complexity of the emplacement in storage and storage's increased density with a small footprint.

INTRODUCTION

The management of spent fuel waste poses a significant challenge for all nuclear power generating countries. Nuclear is the only industry that accounts for all its wastes.

In Canada, nuclear power contributes to over 50% of the total electricity in the province of Ontario and more than 15% overall in this hydroelectricity rich country. All nuclear energy is produced in CANDU (**CAN**ada **D**euterium **U**ranium) reactors that use pressurized heavy water (PHWR) for neutron moderation and cooling.

The natural uranium based CANDU® fuel is used in CANDU® reactors.

Canadian strategy for managing spent fuel from CANDU® Nuclear Power Plants (NPPs) is at reactor (AR) wet storage in spent fuel pools, away from reactor (AFR) at interim dry storage and permanent storage in planned Deep Geological Repositories (DGR) at a suitable location such as the Canadian Shield. The three pronged approach is aimed at preventing potential negative human health impact from the long lived radioactive wastes while maintaining high level of safety.

Various aspects of spent fuel storage with emphasis on CANDU® fuel are discussed below.

DESCRIPTION

The CANDU® Fuel Bundle

The CANDU® fuel bundle is designed with due consideration for easier handling and efficient storage of spent fuel. The natural uranium based CANDU® fuel bundle is small and compact. It is about 0.5 m in length and 10 cm in diameter and weighs about 24 kg (see Figure 1). Zircalloy material is used in the assembly. In contrast, fuel assemblies for some other type of the power reactors can be larger by a factor of ten and weigh twenty times as much.

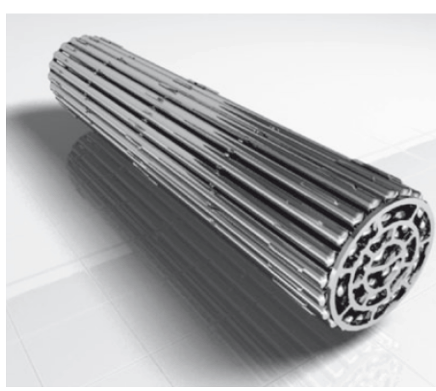

Figure 1 – The 37-Element CANDU® Fuel Bundle

CANDU® Spent Fuel Characteristics [1, 2, 4]

CANDU® reactor is refueled on line without interruption of the production. The fuel burnup at approximately 7 Mega-watts days per kilogram of uranium (MWD/kgU) is typically five times lower than other fuel types in use and consequently results in a larger quantity of spent fuel. However, average decay heat from spent CANDU® fuels after 6 years wet storage is in the 4-6 watts per bundle range which is about five times lower than a typical high burnup spent fuel. This translates to a simpler and cost effective dry storage design.

Compared to other types of fuel, the gamma dose radiation from low burnup CANDU® spent fuels quickly drops to a level permitting use of cost-effective storage systems. Other fuel types continue to emit lethal dose rates > 1 Sievert per hour for about first hundred years thus requiring very specialized transport and storage systems.

Fuel Cycle Optimization

A unique feature of CANDU® reactor technology is its adaptability to utilize fuels other than traditional uranium. Thus CANDU® reactor has the capability to provide flexibility for global fuel cycle strategy optimization. Possible applications include:

- ***Mixed Oxide Fuels:*** Due to the inherent neutron efficiency of CANDU® reactors, wider plutonium isotopic specifications in Mixed Oxide (MOX) fuel could be accepted in CANDU® reactors.
- ***Natural Uranium Equivalent***: This fuel is composed of recycled uranium and depleted uranium. Initial tests have been successfully completed in CANDU® reactor. Full core use is planned in 2014. Use of Thorium and recycled Uranium as alternative fuel is also progressing.

Total inventory of spent fuel and cost of high level waste disposal are important considerations in developing a fuel cycle strategy. CANDU® is an evolutionary reactor with a high degree of fuel cycle flexibility. This enables a country or utility to optimize its fuel cycle strategy based on its own unique circumstances.

CANDU® spent fuel is currently safely stored both in wet and dry storage systems, in licensed storage facilities at individual NPP sites.

Wet Storage

The unique on-power refuelling provision in the CANDU® reactor design enables discharge of CANDU® fuel from the reactor after 12-18 months of irradiation. The compact design and the impossibility of criticality for CANDU® fuel enable a simple and economical interim storage of spent fuel in light water pools. Packing density is determined by heat transfer considerations and not by criticality concerns. Much of the decay heat from the CANDU® fuel is removed within six years of interim storage.

The spent fuel pools are seismically qualified below grade structures provided with a combination of stainless steel and epoxy liners at different NPP stations. The water provides a radiation shielding for the workers. The pool is equipped with a recirculation cooling system that includes heat exchangers, filters and ion-exchange system.

The principal risk in wet storage is that a loss of cooling water would result in fuel sheath burning and resultant criticality issues. Mandatory reviews carried out after the Fukushima incident established that CANDU® reactor design has many inherent features that provide robust mitigation against tsunami type scenarios. Amongst these are fuel related safety features that provide passive cooling of fuel that do not require external power and a larger number of passive water heat sinks relative to other fuel type design.

Because of natural uranium usage and compact design, criticality is not a concern for CANDU® fuels and these can be safely stored in light water pools. This is an advantage over wet storage of other fuel types where addition of neutron absorbers is required and storage density is limited by criticality concerns.

Overview of Candu Energy Dry Spent Fuel Storage Technology Development [3]

The Candu Energy spent fuel storage technology evolved and continues to evolve according to specific project or market requirements. Extensive research and safety analyses have been carried out during last four decades with many actual validation tests carried out at AECL's Whiteshell and Chalk River Laboratories. The technology is well positioned to suit new scenarios and challenges.

Current locations of NPPs in Canada where spent fuel storages are located are shown below:

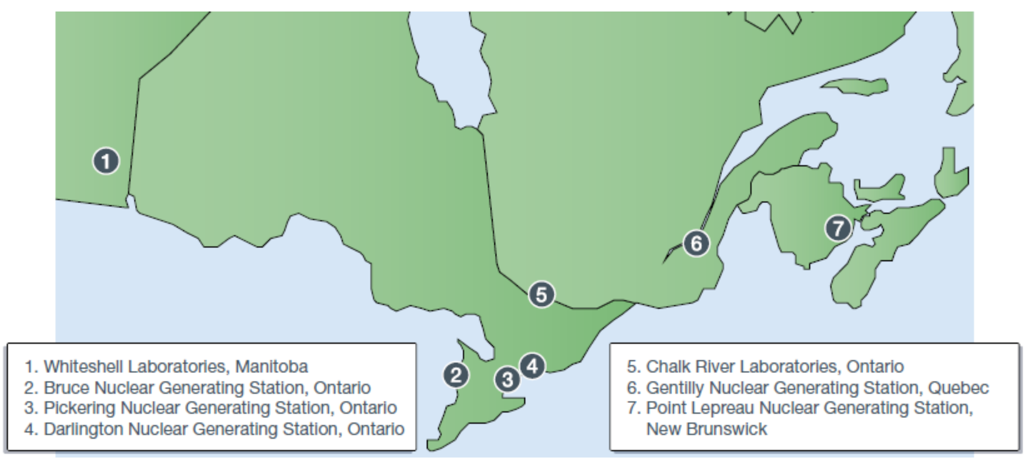

Figure 2 – Spent Nuclear Fuel Storage Sites in Canada

A brief chronological overview is presented below:

The technology for above ground spent fuel dry storage in Concrete Canisters (CC) was introduced during 1970s at the Whiteshell Laboratories (WRL). The original purpose was to store the short WR-1 reactor fuel bundles made with unique Uranium Carbide fuel pellets. The short fuel from the WR-1 research reactor was stored in CC with capacity for 6 fuel baskets, each containing up to 37 fuel bundles in vertical position. The CCs were hollow, structurally continuous reinforced concrete masses standing on concrete pads. These were filled with helium cover gas and seal welded after loading thus providing double containment. Cooling was by conduction and natural convection. The basic technology was thorough and handling tools concepts developed then are still applicable.

The journey for dry storage of prototype CANDU® fuel started in earnest during the early 1980's. These activities were triggered by the following factors:

- Likelihood of having permanent disposal repository in the foreseeable future diminished;
- In the Canadian context, dry spent fuel storage at individual power plant sites was found more feasible than having a large centralized storage site. This was due to high cost of constructing and maintaining a centralized facility, high cost and potential impediments in transportation of spent fuel and societal considerations.
- The option of constructing secondary storage pools at site became uneconomical due to high cost and operational demands.

The CC technology continued to be developed and applied for onsite spent fuel storage at AECL prototype reactors. Original WRL storage capacity of 6 fuel baskets per CC was increased to 8 for Gentilly-1 and then to 9 baskets for Douglas Point and the Nuclear Power Demonstration (NPD) reactor sites.

These spent fuel dry storage developments were ground breaking with Douglas Point having the distinction of being the second largest storage facility after Wylfa in the United Kingdom.

Figure 3 – Concrete Canisters at Douglas Point Decommissioned Facility

The CC usage was extended for dry storage of CANDU® 6 spent fuel bundles at the Point Lepreau Generating Station (PLGS). Client requirement was for a storage capacity of 540 CANDU® fuel bundles after 7 years of wet storage. Thermal tests were carried out in a full scale heat transfer facility before installation. Subsequent installations for similar CCs followed at the Wolsong NPP in Korea.

The mid-1980s saw a flurry of activities related to the development of interim dry spent fuel storage facilities both in and outside Canada. Salient Research & Development (R&D) activities at Candu Energy/AECL included the following:

- In collaboration with specialized companies in the United States (US), AECL helped in developing an air cooled concrete canister, the Ventilated Storage Cask (VSC) that was successfully tested at the Idaho National Engineering and Environmental Laboratory (INEEL).
- A modular storage design was developed by AECL jointly with a US company, in response to the centralized Monitored Storage System (MRS) project in US aimed at serving all US commercial nuclear plants. Several design developments led to the 8-pack which was a 2x4 array of fuel canisters using single containment with a bolted lid . This was designed to hold 12 PWR assemblies and validation tests were conducted at WRL for different power levels.
- In response to the US Department of Energy (DOE) requirement for dry storage of Three Miles Island fuel debris, AECL developed a conduction concrete canister equipped with a vented containment system.
- A cask with a unique re-entrant air inlet and a heat shield protecting the concrete was developed to store the DOE Multi-Purpose container.
- AECL obtained a contract to document the potential use of the conduction concrete canisters for dry storage of High Flux Irradiation Reactor (HFIR) cores.
- AECL participated in the initial bid for the large 3,000 MTU Hanford K-basin fuel packaging and storage project.

The MACSTOR® Module

Early on in the development of dry storage systems, the need for higher storage densities was recognized. A viable design option was recognized to be the merger of few concrete canisters in one structure while maintaining efficient cooling capability. A ventilated structure can dissipate significantly more decay heat than one that requires conduction of heat through thick concrete. When ventilated air cooling is used, a much larger quantity of fuel can be stored in the storage structure, or alternately, spent fuel with a much larger heat release can be stored. The extensive research and development work carried out in the 1980s for a number of spent fuel and high level waste programs provided the necessary back-up for the development of Candu Energy's flagship MACSTOR® (**M**odular **A**ir-Cooled **STOR** age) technology for dry spent fuel storage.

MACSTOR® 200

The MACSTOR® 200 module consists of 2 by 10 array of storage cylinders, each holding 10 fuel baskets, for a total capacity of 200 baskets (hence the "200" model designation). Figure 4 depicts cross-section of the module. The module holds 12,000 fuel bundles representing a stored inventory of 228 MgU. The MACSTOR® 200 module with the Gentilly-2 specific layout provides a storage density 50% greater than that of the concrete canister. In 1995, Hydro-Quebec preceded with the construction and loading of the first module at the Gentilly-2 CANDU® 6 NPP. There are 9 modules currently in operation at Gentilly-2. MACSTOR® modules at Gentilly-2 station are presented on Figure 5.

In 2001 AECL won an international bid for the supply of dry storage technology for the spent fuel from Unit 1 and 2 of Cernavoda nuclear power station in Romania. The project was completed in 25 months, including supply of fuel handling and packaging equipment, construction of one MACSTOR® module and the initial loading of 10 fuel baskets.

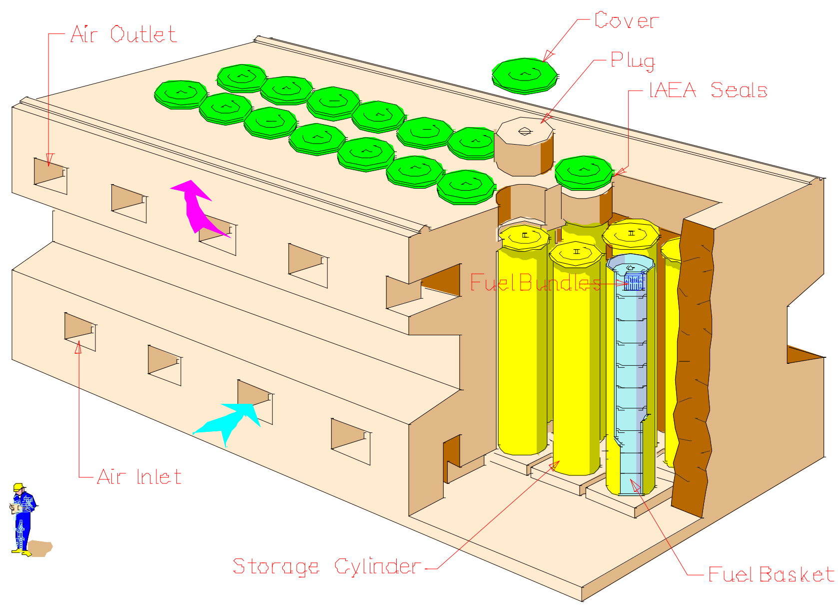

Figure 4-MACSTOR® 200 Cross Section

The Cernavoda storage site is now licensed for the construction of 27 MACSTOR®200 modules, enough for 30 years of operation. There are 5 modules currently in operation at Cernavoda and 1 is under construction.

Figure 5-MACSTOR® 200 at Gentilly-2

MACSTOR® 400

When 3 more reactors were started in South Korea during 1990's it was realised that the storage of spent fuel will become a challenge. The challenge was due to the limited area of the Wolsong dry storage facility and to the limited storage density provided by the concrete canisters. The Korea Hydro and Nuclear Power (KHNP) mandated its subsidiary Nuclear Environment Technology Institute (NETEC) to develop a dry storage structure with a significantly higher storage density than the concrete canister. KHNP-NETEC (KN) selected AECL as the best partner for the joint development of the new dry storage structure. AECL has proposed that KN develop a higher density storage module by horizontally fusing two MACSTOR® 200 storage modules together. The main drivers for new storage system were increased heat dissipating capability and increased storage density of spent fuel. The design effort resulted in development of MACSTOR/KN-400 spent fuel storage module.

The MACSTOR/KN-400 module is a reinforced concrete structure holding 40 storage cylinders laid in four rows of ten storage cylinders. The individual storage cylinders holds 10 fuel baskets, each containing 60 standard CANDU® 6 irradiated fuel bundles. The module thus has a capacity of 400 fuel baskets corresponding to 24,000 fuel bundles corresponding to 456 MgU of spent fuel.

Schematic drawing of MACSTOR/KN- 400 is shown on Figure 6.

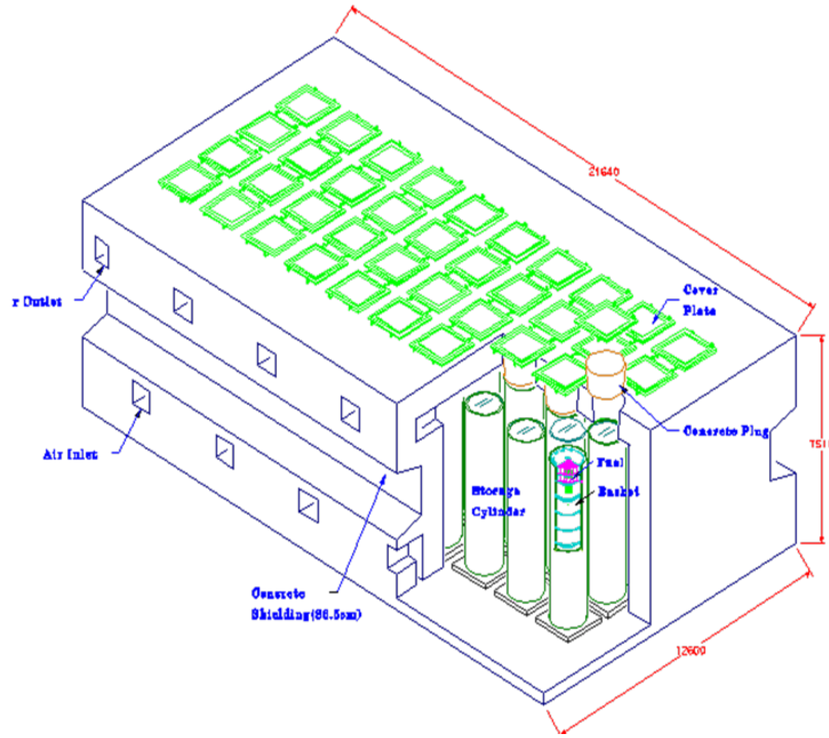

Figure 6-MACSTOR/KN-400 Cross Section

The MACSTOR/KN-400 addressed the conditions that were specific to Wolsong: large annual fuel throughput; space limitations; interfaces with existing fuel preparation facilities; requirement for passive safety; use of double containment; low fuel temperature; and the need for an economical dry storage structure. There are 7 modules currently in operation at Wolsong. Wolsong modules are depicted on Figure 7.

Next MACSTOR® 400 was built at Qinshan (China) on site of new CANDU® reactor. It is similar to Wolsong design. There are 2 modules currently in operation at Qinshan. Design work for transition from MACSTOR® 200 to MACSTOR® 400 at Cernavoda NPP site in Romania has also been completed

MACSTOR® module generic design parameters are presented in following table:

TABLE I – Generic Design Parameters of MACSTOR® Module

PARAMETER	MACSTOR® 200	MACSTOR® 400
Service life of structure	50 / 100 years	>50
Capacity	12 000 bundles	24 000 bundles
Size Length (m) Width (m) Height(m)	 21.6 m 8.1 m 7.5 m	 21.7 m 12.7 m 7.5m
Module heat release	73kW	146 kW

Figure 7-MACSTOR/KN-400 at Wolsong

Main features of MACSTOR® module are:

- The storage cylinder is made of corrosion resistant material (zinc-coated carbon steel and stainless steel top portion). Once filled with spent fuel baskets, its top is welded to the storage cylinder.
- The bottom section of the storage cylinder interfaces with seismic restraints to allow free thermal expansion of the storage cylinder in the vertical direction, while restraining movements in the horizontal direction
- The top of the storage cylinder is seal welded after loading and provided with a welded weather cover to protect the shield plug from elements
- Cooling of the storage cylinders is achieved by natural convection and infrared radiation from the storage cylinder surface and by conduction to the module's upper deck. Cooling air enters the plenum through large openings at the bottom and escapes from the top.
- The MACSTOR® module is designed to withstand credible loads and hazards.
- The concrete is protected from direct infrared heating from the storage cylinders by thermal insulation panels covering the internal ceiling below the upper deck and the upper portion of the walls of the module down to above the air inlets
- The module has no moving parts and has no failure mode in normal operation

Safety characteristics of the MACSTOR®

The MACSTOR® module stores spent fuel for intermediate storage and is capable of adapting to future needs to move fuel to a permanent repository whenever required. Some safety features include:

- The MACSTOR® module provides excellent shielding resulting in low dose rates to personnel as there are no shielding compromises from the need to move the structure.
- The MACSTOR® module provides two physically separate engineered containment boundaries: the fuel basket and the storage cylinder. Failure of either containment boundary will not result in failure of containment function to the fuel assemblies thus providing a passively safe containment system.
- The MACSTOR® module is provided with a simple but effective monitoring system that enables early detection of a potential leakage from the fuel basket and storage cylinder.
- The module has seals, re-verification tubes and receptacles provided to enable inspections required by the International Atomic Energy Agency (IAEA) as a safeguards feature. It includes measuring the gamma dose rate and spectrum of each irradiated fuel basket when the cylinders are loaded with spent fuel.

Advantages of Dry Storage Method over Wet Storage

Economics of utilizing available dry storage technology versus expansion of wet storage capacity becomes an important consideration once the wet storage pools approach full capacity utilization.

Sequential construction of large storage pools near NPP sites is an expensive proposition and local regulations can also be an impediment.

Overhead costs associated with spent nuclear fuel storage at an operating NPP can be easily integrated with operating costs as the marginal cost is relatively small. Due to the relatively small mass and volume of spent fuel, the cost of spent fuel management including disposal is only about 1 – 2% of the cost of electricity.

Candu Energy Dry Storage System Upgrade and Adaptation for Other Applications

Although the current MACSTOR® spent fuel dry storage systems are providing the intended service satisfactorily, efforts are on-going at Candu Energy to identify areas of improvement for even better product. Some of these considerations are mentioned in brief as follows:

- ***Increased Storage Density*** – Presently, 10 storage baskets (600 fuel bundles) are stored in each of the 40 cylinders in the top of line MACSTOR® 400. Several modifications, such as, varying the basket dimensions and modified loading mechanism can be considered to increase capacity without affecting the safety and load bearing capability of the storage cylinder. Such improvements will be very cost effective for sites where storage area is limited.
- ***Enhanced Shielding*** – Available area and hence capacity for spent fuel dry storage modules can be increased if the site fences could be brought closer to the storage modules. Shielding enhancements at critical locations on the module could significantly improve the module site foot print. Other enhancements can be implemented through provision of shielding boxes made from a number of vertical steel plates placed at optimum distances away from the air circuit. Figure 10 shows a cut-out-section of MACSTOR®.

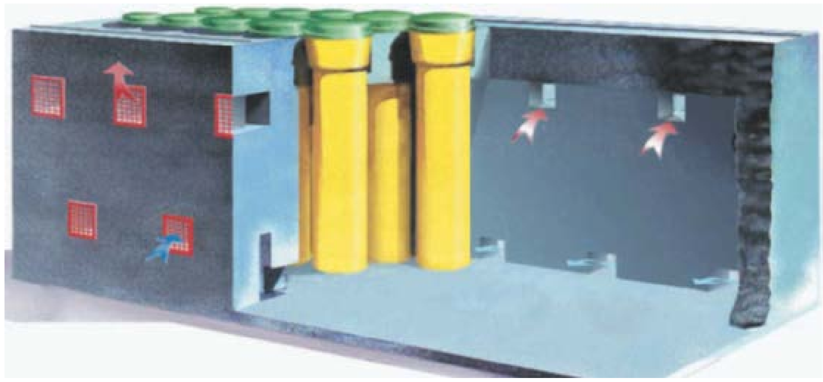

Figure 8 – Cut-out-section of MACSTOR® module

- ***Higher Power Rating MACSTOR® Module*** - For MACSTOR® applications at sites having sustained high ambient temperature or for specific applications requiring spent fuel removal from wet storages before the normal 6-year cooling period, several modifications can be made to accommodate the higher heat load while maintaining the bulk concrete temperature within limits. Heat transfer studies have been carried out for MACSTOR® modules with few modifications with encouraging results.

- ***MACSTOR® module for LWR fuel*** – A lot of development work for non-CANDU® spent fuel storage in MACSTOR® module has been carried out. Details for single containment and double containment configurations with light water reactor (LWR) fuel was assessed in experiments done at AECL's White shell Laboratories. A payload of 12 pressurized light water fuel assemblies at about 15 to 20 kW per fuel canister was evaluated for a double containment configuration. To maintain acceptable concrete temperature, improved air circulation was considered. Advantages and flexibility of a double containment module include
    - protection from salt brine in plants located in coastal areas and consequently lower material cost;
    - Sensitive leak detection capability;
    - Maintaining containment boundary even if small quantity of helium leaks from the fuel canister;
    - The upper deck and walls can be divided in two structures. The internal shielding upper deck would hold the storage cylinder operating at relatively high temperature. The second upper deck would be the structural slab that handles the mechanical loads. Thermal hydraulic modeling for this configuration indicate acceptable thermal gradients in the reinforced concrete;
    - Such higher power MACSTOR® modules may be considered for use in long term centralized spent fuel storage facilities.

- ***Application of MACSTOR® Module for Low and Medium Level Waste Packages*** – Various types of radioactive wastes generated from operating commercial reactors, decommissioned facilities, nuclear laboratories and similar facilities are stored in containers of various types. Typical packaging and contents are shown in Table II.

TABLE II – Typical Waste Packages and Contents

Waste Packaging	Typical Contents	Overall Dimensions	Materials
500 litre drum	Operational ILW, both solids and liquid/sludges	800 mm diam. x 1200 mm height	Austenitic stainless steel
3 m^3 box	Operational and decommissioning solid ILW	1720 mm x 1720 mm x 1255 mm height	Austenitic stainless steel
3 m^3 drum	Operational and decommissioning liquid/sludge ILW	1720 mm diam. x 1255 mm height	Austenitic stainless steel
4 metre box	Large items of decommissioning waste	4013 mm x 2438 mm plan x 2200 mm height	Austenitic stainless steel

MACSTOR® technology can be adapted for safe and cost-effective storage of different waste packages. MACSTOR® module and its smaller retube canister version can be adapted to store radioactive waste drums 500 liters to 3 cubic metre capacities. The module is made from regular density concrete and holds storage cylinders made from corrosion resistant material. A loading interface device is used to facilitate stacking the drums in the storage cylinders.

MACSTOR module concept can also be applied for safe storage of box packages. The box package contains operational and decommissioning wastes that can be both solids and liquid sludges. Loading of boxes can be accomplished using the transfer flask and loading interface device providing adequate shielding during loading operations.

- ***Filter Storage Vaults*** – Figure - 9 shows a filter flask being loaded into a filter storage vault in one of the operating CANDU® stations. The filters originate from the nuclear power plant cooling systems.

Figure 9 – Filter Flask and Filter Storage Vault

The above is just a brief overview of Candu Energy's dry storage technology and points to its adaptability to a wide range of specific customer applications in the nuclear power industry. Candu Energy has already been actively involved in design and management of low, medium and high level wastes since the inception of nuclear technology in Canada. Several of these applications are depicted in Figure 10.

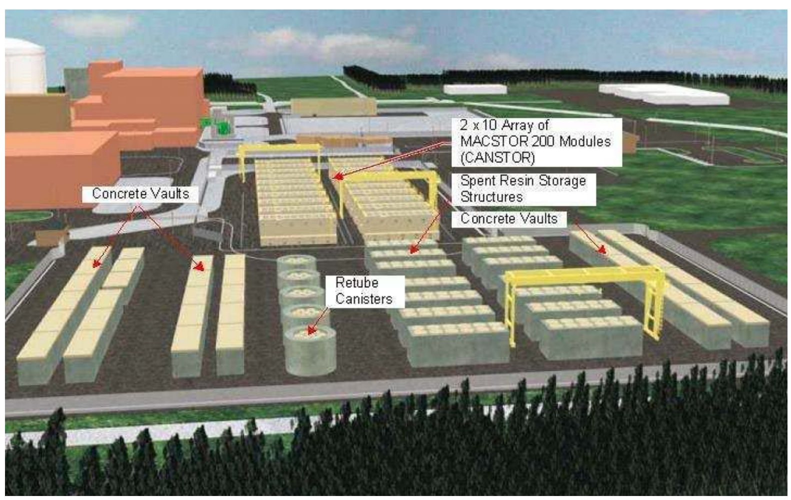

Figure 10 – Illustration of CANDU® 6 Waste Management Facility with MACSTOR® Technology planned for Gentilly-2 (Canada)

CONCLUSION

Candu Energy Inc. is built on the foundation of more than five decades of nuclear innovation and is owned by a company that has solid commercial and construction project credentials. The spent fuel storage technology evolved from extensive research and development program started almost at the company's creation. Candu Energy has depth of experience in design of different types of dry storage system for spent nuclear fuel. Each new project benefited from the experience gained from previous project. During evolution period, the capacity of storage structures has been increased by a factor of almost 250, from the initial design to the most recent facilities. Evolution was accomplished while maintaining stringent safety and environmental criteria and while achieving low construction and operating costs. This development also opened new venues for applying the technology to a variety of waste management solutions.

As a member of Organization of Canada nuclear industries (OCI), that includes a wide spectrum of manufacturers and service providers, the company can readily assist in meeting specific customer demands related to the nuclear industry. The storage facilities operation has been event free to date. The development of dry storage technology at Candu Energy Inc. will continue to progress and to provide its clients, with safe and economic management of the spent fuel bundles for years to come.

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