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Update on Use of AECL's MACSTOR Module at CANDU 6 Stations

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ABSTRACT

AECL has contributed to the technology development and implementation of dry spent fuel management facilities in Canada and internationally over the last three decades. During that period, AECL has designed a number of concrete canister models and the MACSTOR® module; a medium size air-cooled vault. AECL's dry storage technology was used in Canada, Korea and Romania for the construction of eight large-scale above ground dry storage facilities for CANDU® spent fuel. These projects add up to a constructed capacity in excess of 5,000 MgU, that represents a significant share of the total worldwide dry storage capacity.

This paper describes basic research and technology developments made at AECL's facilities to develop those dry storage technologies for its own reactors and for the operating CANDU 6 reactors. The current operating status of the facilities using concrete canisters is provided. A description of the MACSTOR 200 modules each having a capacity of 228 MgU that is in use at the Gentilly 2 and Cernavoda stations is provided. The Cernavoda spent fuel management facility was commissioned in 2003. The organisational, licensing, equipment supply and construction aspects that were necessary to deliver this turnkey project by AECL and its Romanian partners in 25 months are described. The paper also provides an outline of the joint program between AECL and KHNP-NETEC to develop the new MACSTOR/KN-400 and provides a description of this module having a capacity of 456 MgU (thus twice the MACSTOR 200 capacity) to be deployed by 2007 at the Wolsong site in Korea.

I Interim Storage of Spent Fuel

The Canadian strategy for managing the used fuel from Canada's CANDU nuclear power plants has been to provide safe interim storage at the reactor sites, and in parallel to develop the technology for disposal [1]. The site storage is provided by a combination of pool and dry storage technologies.

When a CANDU fuel bundle is discharged from the reactor after 12-18 months of irradiation, it is removed to a pool system for interim storage. The water in the pool removes the residual heat produced by the spent fuel and provides radiation shielding for workers. The small size of the CANDU natural uranium fuel bundle, and its impossibility of achieving criticality in light water, permit a simple and economical pool design. The fuel packing densities are thus mainly determined by considerations such as heat transfer, shielding, and seismic design, and not by the need to avoid criticality accidents.

After spent CANDU fuel has been cooled in wet storage for about six years, its activity and rate of heat generation have decreased sufficiently to allow the fuel to be transferred to dry storage. Dry storage offers a number of advantages over wet storage: passive storage conditions; ease of expansion; simplicity; and low construction and operating costs.

AECL pioneered the development of above ground dry storage technology in the 1970's, and has since installed 8 dry storage facilities at both domestic and overseas nuclear stations. Dry storage facilities using concrete canisters were first implemented at AECL's research and prototype reactor facilities: Whiteshell Laboratories (WL); Chalk River (CRL); and at AECL's decommissioned Gentilly 1 and Douglas Point reactors.

Since completion of those early projects, the technology has been expanded to operating CANDU 6 stations. At the end of the 1980's, a larger capacity concrete canister was designed, and implemented at the Point Lepreau and Wolsong stations. More recently, the MACSTOR 200 modular vault has been designed, with a capacity of 228 MgU CANDU fuel. It is in use at the Gentilly 2 and Cernavoda stations. A larger version of the module, the MACSTOR/KN-400, is being designed for use at the Wolsong station.

II Development of the Concrete Canisters

Initial Development - Storage of Research and Prototype Reactor Fuels

AECL began its dry storage studies at the Whiteshell Research Laboratories in the early 1970s. Silo-like structures called concrete canisters were first developed for the storage of enriched uranium fuel from research reactors. The concrete canister concept was then further developed for spent CANDU natural uranium fuel, and was subsequently applied to the prototype Gentilly 1, Douglas Point and Nuclear Power Demonstration reactors as they were being decommissioned. By 1989, all 457 metric tonnes of spent Uranium fuel (MgU) accumulated during the operation of these reactors was safely and economically stored in dry concrete canisters (see first three columns of Table II-1).

CANDU fuel bundles, after a sufficient period of decay, release only a few Watts per fuel bundle. This low heat generation facilitates the design of dry storage structures operating at low fuel temperature. This permits the use of air as the cover gas for the fuel bundles, without compromising fuel integrity. The absence of any need for an inert cover gas results in a simpler and lower cost fuel packaging process.

Each concrete canister contains a stack of spent fuel baskets, similar to the one shown in Figure II-1. The spent fuel basket is a stainless steel container that holds a number of vertically positioned fuel bundles. The fuel baskets are contained in a storage cylinder (liner) within the canister; the cylinder serves both as formwork for construction of the canister, and as an additional containment barrier for the fuel. The AECL concrete canister therefore provides double containment of the fuel bundles: the seal welded fuel basket provides the first containment, and the seal welded concrete canister liner provides the second. With a double containment system, even the unlikely failure of a particular envelope is benign and does not result in a release of volatile radionuclides.

The concrete canister is provided with a monitoring system to sample air from the storage cavity (liner), and thereby verify the integrity and function of both containment boundaries. Dry storage structures using double containment thus offer passive safety in the event of failure of a containment envelope.

Table II-1 General Parameters of Canadian Commercial Dry Storage Facilities

PARAMETER	**Whiteshell Research Laboratories**	**Gentilly 1**	**Douglas Point, NPD**	**Point Lepreau, Wolsong**	**Gentilly 2, Cernavoda**
Year of first storage	1976	1985	1987, 1989	1991, 1992	1995, 2003
Storage technology	Concrete canister (2.6 m O.D.)	Concrete canister (2.6 m O.D.)	Concrete canister (2.6 m O.D.)	Concrete canister (3.1 m O.D.)	MACSTOR 200 module
Bundle size	8.18 mm O.D	10.2 mm O.D	8.18 mm O.D	10.2 mm O.D	10.2 mm O.D
Fuel	2.4 / 2.25 wt % ^{235}U	Natural U	Natural U	Natural U	Natural U
Fuel material	UO_2 / UC	UO_2	UO_2	UO_2	UO_2
Number of bundles per basket/module	23	38	54	60	60
Number of baskets per concrete canister or per storage cylinder	6	8	9	9	10
Total capacity per concrete canister or per storage cylinder (bundles)	138	304	486	540	600
Total storage capacity per structure (MgU)	1.83	6.35	6.46	10.3	228
Cover gas	He	Air	Air	Air	Air
Containment	Double	Double	Double	Double	Double

Fuel Transfer

The dry storage process begins with fuel preparation activities in the spent fuel pool and in a Shielded Work Station (SWS). Assorted tools and lifting equipment are used for fuel basket loading and handling operations.

The fuel bundle handling equipment is located on in-pool worktables. Spent fuel bundles are transferred from pool storage trays into fuel baskets that can hold 60 bundles (at CANDU 6 stations) in a vertical position:

- A manually operated fuel bundle tilter moves 12 of the 24 bundles on a tray from horizontal to vertical position.
- A manual bundle lifting tool is then used to transfer the fuel bundles, one at a time, from the tilter to the fuel basket.

Once filled, the basket is moved under the SWS chute and lifted out of the spent fuel pool into the SWS.

The SWS is located on the edge of the spent fuel pool and is a massive shielding structure made from steel structural members, steel lined lead panels and polyethylene panels. It houses the equipment necessary to dry the fuel, weld the fuel basket, and inspect the welds. A transfer flask and a transporter are used to move the fuel basket from the SWS to the dry storage site located on the plant site.

Concrete Canisters for Commercial Power Reactors

The same basic concrete canister technology developed for research and prototype reactors, was applied to the first facilities for on-site dry storage of spent fuel generated at operating CANDU 6 plants.

Due to the significantly larger inventories generated by power reactors, a larger fuel basket was designed to hold 60 CANDU-6 fuel bundles (1.1 MgU). This corresponds to a 60% capacity increase compared to the earlier concrete canister design used in AECL's prototype reactor storage facilities. The CANDU 6 fuel basket is shown in Figure II-1. To accommodate the larger basket, a larger diameter concrete canister was designed; the canister capacity of 9 baskets was maintained, providing a total capacity of 540 fuel bundles.

Table II-2 Capacities of Dry Storage Facilities Using AECL's Technology

PLANT	Fuel Quantities (MgU)	Number of Storage Structures (As of 2005)	Number of Storage Structures (Lifetime)
WL [1] (Canada)	17	16	
Gentilly-1 [1] (Canada)	67	11	
Douglas Point [1] (Canada)	298	47	
Nuclear Power Demonstration [1] (Canada)	75	11	
Pt. Lepreau (Canada)	1436 2790 (lifetime)	140	275
Wolsong-1 to 4 (Korea)	2052 2790 (lifetime)	200	280 (up to 2007)
Gentilly-2 (Canada)	1140 2790 (lifetime)	7	16
Cemavoda 1-2 (Romania)	228 6156 (lifetime)	1	27

(1) Decommissioned

The thermal performance of the CANDU 6 fuel basket was tested in a full-scale facility at AECL's Whiteshell Research Laboratories. The tests demonstrated an adequate steady-state storage temperature, to assure long term integrity of the fuel using air as the cover gas.

New Brunswick Power and Korea Electric Power Company selected this larger concrete canister for their CANDU 6 nuclear generating stations at Point Lepreau (1989) and Wolsong 1 (1990) (see Table II-2). The Point Lepreau/Wolsong concrete canister is shown in Figure II-2. This concrete canister model is currently used to store more than 3,400 MgU of spent CANDU fuel; this constitutes one of the largest inventories worldwide of spent fuel. The modular nature of concrete canisters allows the owner to build them according to the demand; for example, construction of 80 new units at Wolsong will be made shortly.

Courtesy of SIGAMA Ltd.

Figure II-1 Basket Holding 60 CANDU Spent Fuel Bundles

Figure II-2 The Point Lepreau Concrete Canister

III Development of the MACSTOR Module

Early on in the development of dry storage systems, AECL recognized the need for higher storage densities to accommodate the larger spent fuel inventories of operating stations. The 10.3 MgU capacity of the Point Lepreau concrete canister fulfilled this need as it significantly increased the storage density over the earlier canister design. This concrete canister technology continues to be suitable for the Point Lepreau site.

Some other stations, however, do not have as much land available as Point Lepreau. Gentilly-2, Wolsong, and Cernavoda, for example, have more limited land availability; Wolsong and Cernavoda are particularly challenging given their topography and multiple reactor units. To further increase the storage density, AECL began the development of a ventilated air-cooled storage structure. The technology was named MACSTOR (from Modular Air-Cooled STORage).

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.

To minimize modifications from the earlier concrete canister design, the MACSTOR configuration consists of a small array of storage cylinders - similar to the liners used in the concrete canisters - assembled together in a single monolithic structure. The module has large air inlets and outlets, laid out as labyrinths for shielding, on each side of the structure. The cooling air, driven by natural convection, enters through the bottom air inlets and exits through the top air outlets.

A full scale MACSTOR test facility was built at AECL's Whiteshell Laboratories. Numerous tests were conducted to confirm the efficient thermal performance of the design for both normal air flow and postulated air flow blockage conditions. The tests simulated the heat releases expected from spent CANDU 6 fuel. AECL also performed a separate series of tests at higher thermal powers and with a larger air circuit, to simulate typical storage conditions for other fuel types, such as those expected when storing fuel from PWR, RBMK and VVER reactors. The tests also facilitated design improvements such as enhanced air-flow circuit geometry, and improved shielding.

The MACSTOR 200 module has a 2 by 10 array of storage cylinders, each holding 10 fuel baskets, for a total capacity of 200 baskets (hence the "200" model designation). The module holds 12,000 fuel bundles representing a stored inventory of 228 MgU. In 1995, Hydro-Québec proceeded with the construction and loading of the first module at the Gentilly-2 CANDU 6 nuclear generating station (see Figure III-1). The MACSTOR 200 design parameters are provided in Table III-1, along the ones for the MACSTOR/KN-400 module covered in Section V.

The MACSTOR 200 module with the Gentilly 2 specific layout provides a storage density 50% greater than that of the concrete canister.

Figure III-1 Typical MACSTOR Dry Storage Module Site – Gentilly 2

The MACSTOR 200 module is also the reference design for storage of spent fuel from the Advanced CANDU Reactor (ACR) line of reactors. The ACR MACSTOR design retains a configuration with 200 fuel baskets, but the number of fuel bundles has been lowered to 36 per basket, to maintain the reference thermal envelope for the ACR's enriched uranium fuel.

Table III-1 Design Parameters of MACSTOR 200 and MACSTOR/KN-400 Modules

PARAMETER	MACSTOR 200	MACSTOR/KHNP-NETEC-400
Plant applicability	Gentilly 2 Cernavoda	Planned for Wolsong 1 to 4 Units
Service life of structure	50 / 100 years	50 years
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 7.5 m
Minimum fuel cooling time	6 years	6 years
Module heat release	73 kW	146 kW

IV The Cernavoda MACSTOR Dry Storage Facility

The Cernavoda nuclear power station, which is operated by *Societatea Nationala Nuclearelectrica S.A.* (SNN), is sized for five CANDU 6 reactors. The first reactor has been in commercial operation since December 1996, and the second one is planned to be in service in 2006. The spent fuel bundles from Unit 1 are stored in its spent fuel pool, which can accommodate about 8 to 10 years of plant production, depending on plant capacity factor and fuel burnup.

In the year 2000, SNN solicited international bids for the supply of dry storage technology for the spent fuel from Cernavoda Unit 1 (and eventually Unit 2). The call for tenders thus encompassed a planned inventory of more than 6,000 MgU of spent fuel. The MACSTOR 200 system emerged from the many competitors that tendered bids as the most suitable and most cost effective technology. AECL managed the complete project on a turnkey basis using experienced Romanian and Canadian suppliers. The Cernavoda storage site is now licensed for the construction of 27 MACSTOR 200 modules, enough for 30 years of production from both Unit 1 and 2. The Cernavoda MACSTOR 200 module is shown in Figure IV-1.

This project benefited significantly from the long term relationship between Romania and Canada, and from the mature Romanian nuclear industry. Local Romanian companies, such as SITON for engineering and licensing documentation work, and Nuclearmontaj for procurement work and construction, supplied about 85% of the labour and equipment for the facility. The project started in 2001 and was completed on schedule within 26 months of the contract effective date, with first spent fuel loaded in May 2003. The completion of this project within such a short schedule is a tribute to the experienced personnel active in the Romanian nuclear industry. Also, the selection of a turnkey approach can be seen as the principal decision that facilitated the seamless project implementation summarized in Table IV-1. SNN is now fully autonomous in performing fuel transfer operations, supplying future storage equipment, and building new modules [2].

Table IV-1 Project Schedule of Cernavoda Dry Storage Facility

EVENT	DATE
Contract effective date	April 9, 2001
Construction licence obtained	June 6, 2002
First fuel loading	May 27, 2003

Unit 1 is maintaining an excellent capacity factor, and two more MACSTOR 200 modules are planned to be built in 2006.

Figure IV-1 The Cernavoda MACSTOR Dry Storage Facility in Romania

V Development of the MACSTOR/KN-400 Module for Wolsong

The management of spent fuel is an important consideration of the Korean nuclear industry to ensure the continued use of this safe and environmentally friendly source of electricity. Korea Hydro and Nuclear Power (KHNP), has been operating a CANDU reactor at the Wolsong nuclear power station since 1983. In 1991, KHNP implemented a dry storage system based on concrete canisters designed by AECL, and built by Hyundai Engineering Company Ltd. The Wolsong dry storage site currently has the largest installed capacity in Asia.

During the 1990's, 3 more reactors were started at the Wolsong station. When those spent fuel pools approach their design capacity (i.e. 2006-2009), new storage space for up to 20,000 spent fuel bundles produced every year will need to be available. The dry storage of this fuel represents a challenge due to the limited area of the Wolsong dry storage facility and to the limited storage density provided by the concrete canisters.

KHNP has mandated its subsidiary Nuclear Environment Technology Institute (NETEC) to develop a dry storage structure having a significantly higher storage density than the concrete canister. After a series of technical and economic evaluations, KHNP-NETEC (KN) selected AECL as the best partner for the joint development of the new dry storage structure [3].

AECL has proposed that KN develop a higher density storage module by horizontally fusing two MACSTOR 200 storage modules together. The proposed configuration minimizes modifications to the reference MACSTOR 200 design, and so facilitates the design and licensing process in Korea. As the new module would hold 400 fuel baskets, it was labelled the MACSTOR/KN-400. Both KHNP-NETEC and AECL participated to the conceptual development of the MACSTOR/KN-400 module.

The main change from the reference design is that the new module will have 4 rows of 10 storage cylinders, instead of 2 rows. It thus will provide a capacity of 24,000 bundles, corresponding to 456 MgU of spent fuel. One module can therefore store slightly more fuel than the entire annual production from the 4 Wolsong reactors. The MACSTOR/KN-400 is illustrated in Figure V-1.

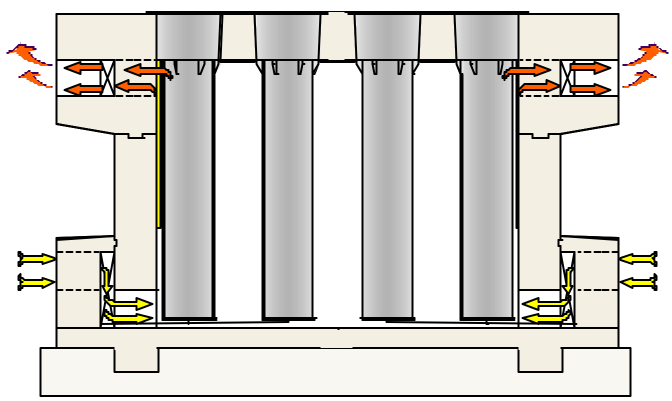

Figure V-1 The Planned MACSTOR/KN-400 for Wolsong 1-4 Reactors (Korea)

The main design challenge of the MACSTOR/KN-400 module is to dissipate the 146 kW residual heat from the stored fuel, twice the thermal power of the MACSTOR 200 module. The same air circuit as the MACSTOR 200 module was retained for the MACSTOR/KN-400, as its performance and shielding characteristics were well understood. The increased thermal power would increase fuel storage temperature and result in higher concrete temperature and temperature gradients.

For the MACSTOR/KN-400 thermal design, AECL has developed a heat transfer model using CATHENA, a thermalhydraulic code used for CANDU reactor heat transfer analysis. The model determined that the MACSTOR/KN-400 air cooling circuit would provide a fuel temperature of 150°C [4], representing only a 15°C increase with respect to the MACSTOR 200 design operating in similar conditions. This fuel temperature is still 10°C lower than that licensed for the Wolsong concrete canisters. The operating temperature of the fuel in the MACSTOR/KN-400 will ensure the integrity of the fuel sheathing for the 50 years service life of the facility [5].

The higher heat load of the MACSTOR/KN-400 also requires the addition of Thermal Insulation Panels on internal surfaces of the concrete, to limit thermal gradients and stresses in the concrete. This simple modification significantly reduces thermal stresses and makes the MACSTOR/KN-

400 structure capable of handling stresses from normal and abnormal loads, and from postulated Design Basis Events such as an earthquake.

The MACSTOR/KN-400 addresses the conditions that are 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. Depending on the final storage site configuration, the MACSTOR/KN-400 is expected to offer a storage density that is about 3 times larger than provided by the existing concrete canisters, while providing slightly lower costs.

In 2005, the MACSTOR/KN-400 project is moving into the detailed engineering and licensing phase, to allow KHNP and its subcontractors to proceed with the construction of the first MACSTOR/KN-400 module in 2007.

VI Summary

The technology necessary for dry storage of spent fuel from the WR-1 research reactor, from the prototype CANDU reactors and from operating CANDU 6 stations was developed from a robust research and development program initiated at AECL's research laboratories. Each new project benefited from the design, licensing, construction and operating experience gained from each previous project. The development was made in a progressive manner over three decades. During that period, the capacity of storage structures has been increased by a factor of 100, from the initial design to the most recent facilities. Those developments were made while maintaining stringent safety and environmental criteria and while achieving low construction and operating costs. The development of dry storage technology at CANDU 6 stations will continue to evolve and to provide AECL's clients, with safe and economic management of the spent fuel bundles for years to come.

VII References

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