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ON THE ESSENTIAL CHARACTERISTICS OF UNDERGROUND STORAGE OF SPENT NUCLEAR FUEL IN THE HI-STORM 100 SYSTEM

K.P. Singh, Ph.D.
President and CEO, Holtec International
555 Lincoln Drive West, Marlton, NJ, 08053, U.S.A.

ABSTRACT

HI-STORM 100 is a vertical ventilated spent fuel storage system certified for use at any U.S. nuclear plant site under the rules of 10CFR72. The HI-STORM 100 System consists of a welded canister installed in a free-standing disposition inside a massive cylindrical body of steel and concrete, referred to as the "overpack" or the "ventilated module", which is equipped with ventilation ducts near its bottom and top. The overpack can be deployed in a free-standing or anchored configuration. Although of a relatively stubby stature (approximately 11 feet in diameter x 18 feet tall with its lid installed), the aboveground HI-STORM 100 System is undoubtedly a conspicuous structure at a plant site. The underground version of the HI-STORM 100 overpack (labeled HI-STORM 100U), due to be certified by the U.S. Nuclear Regulatory Commission (USNRC) in early 2008, renders itself virtually inconspicuous by situating the canister underground. The depth of the canister's location below the grade can be varied to suit the needs of a site, and the extent of physical protection provided to the stored fuel can be increased to the level desired by the facility's owner by appropriately hardening the top lid, which is the only ingress path to the canister storage cavity.

While the vertical ventilated module design undergoing certification by the USNRC is expressly engineered to store Holtec International's canisters, it can also, in principle, be used to store other canisters in use around the world. In other words, HI-STORM 100U can serve as the universal vessel for storing all canisterized fuel in the world, making it a meritorious candidate for large autonomous storage sites such as the U.S. Department of Energy's planned Aging Facility.

The underground storage technology may also be particularly appealing to high seismic zone countries such as Japan and Taiwan, and in regions where nuclear plant sites are constrained by paucity of excess land or those located close to population centers, such as many in Europe.

KEYWORDS

Underground storage, HI-STORM, Spent Nuclear Fuel

INTRODUCTION

A spent fuel storage system that is inherently safe against all forms of terrestrial threats has emerged as a pressing need in the 21st Century as the quantity of used nuclear fuel discharged by the world's reactors continues to accumulate at an ever greater rate. Adding to the technical challenge of safe fuel storage is the fact that operating lightwater reactors are burning increasingly more enriched fuels, which means that the radiological potency of the used fuel being discharged from the commercial reactors is also rising. Holtec's vertical ventilated storage system, referred to as HI-STORM 100, adopted by some 50 nuclear reactors worldwide thus far, tackles the issue of minimizing dose accreted by the storage of high burnup fuel by permitting the user to place extremely dense shielding concrete (up to 200 lb/cubic feet) in the module and by permitting regionalized storage of fuel in the canister [1].

Protection of the physical integrity of the stored canister in the face of a striking projectile (or crashing aircraft) is achieved by utilizing a dual-shell steel weldment (in lieu of reinforced concrete) as the structural backbone of the HI-STORM overpack. These design measures have enabled HI-STORM 100 to receive the official imprimatur to store fuel with high burnups (viz., PWR fuel ≤68.2 GWD/MTU) [2] and to successfully protect the stored canister against a crashing F-16 fighter plane laden with fuel [3]. Thus, while the aboveground HI-STORM 100 system meets the needs of today with ample margins, the nuclear industry, its fortunes inextricably tethered to public acceptance, must look ahead when the postulated threats to the spent fuel installations are likely to become more energetic. The migration of the aboveground HI-STORM to the underground, described in this paper, is largely driven by this emerging need to secure public acceptance in the post 9/11 age by devising a storage system of transparently incomparable robustness.

In a broader sense, physical ruggedness is only one of what this writer refers to as "four quests for zeros" in dry storage of spent nuclear fuel, namely: zero dose to the environment; zero risk of radiological release under long-term storage and under all imaginable threats; zero risk of a radiation release from a handling accident, and zero risk of damage to the fuel in long-term storage. The HI-STORM 100U underground vertical ventilated module is engineered to realize the industry's goal of approaching the above four zeros for storing spent nuclear fuel and all other forms of high-level waste.

A summary description of the HI-STORM 100U VVM is given that provides the necessary information base to the reader to fully appreciate its functional attributes.

BACKWARDS COMPATIBILITY

The HI-STORM100U VVM is *completely* compatible with all other dry storage capital equipment provided by Holtec International that are in use at the spent fuel storage facilities around the world. All Holtec multi-purpose canister models will fit in HI-STORM 100U and can be loaded in it using the same HI-TRAC transfer cask that is used to load the aboveground HI-STORM. HI-STORM 100U does not require any new custom ancillary equipment for loading or maintaining the storage facility.

While HI-STORM 100U uses the same transfer cask (HI-TRAC) and ancillaries for canister transfer as the HI-STAR dual-purpose overpack or other HI-STORM models, the "100U"/HI-

TRAC interface surface is near ground level (Figure 1), making the transfer operation more operator-friendly. Vertical canister insertion and removal eliminates any concern of friction posing a problem, during canister initial loading and more importantly during removal of the canister after many years of open-air storage.

A storage facility deploying the HI-STORM 100U VVM may use an unlimited number of VVMs as can be inferred from Figure 1. The preferred embodiment of the VVM array is a rectangular grid of equal minimum pitch or spacing. The minimum spacing is 12 feet center-to-center between adjacent modules, and ensures that any of the commercially available cask transporters can traverse the VVM arrays in either of the two orthogonal directions, providing autonomous access to each stored canister.

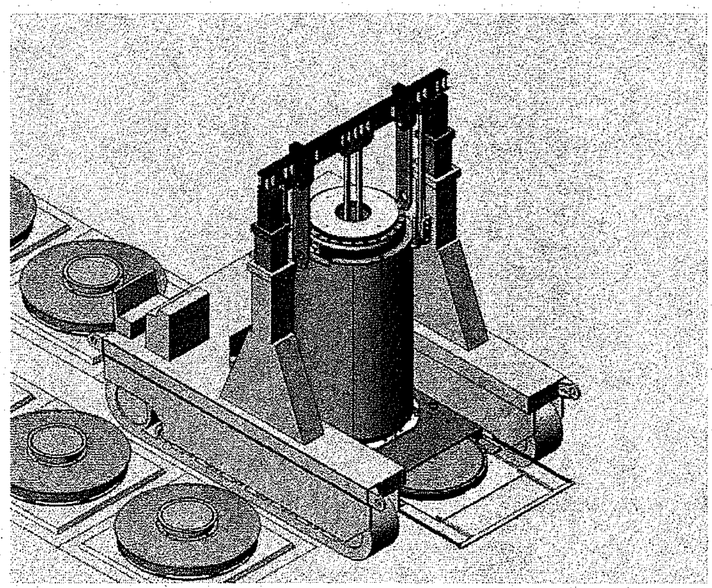

Figure 1. A Cask Transporter Shown Over One VVM Cavity Ready to Transfer a Canister in an Array of VVMs

This minimum spacing also serves to provide adequate shielding around each storage cavity. No limit is placed on the maximum spacing.

DESCRIPTION ATTRIBUTES OF THE HI-STORM 100U VVM

The HI-STORM 100U VVM, like HI-STORM 100 [5] and HI-STORM 100S [6] overpacks, is a vertical, ventilated dry spent fuel storage system engineered to store canisters containing spent nuclear fuel. Each VVM stores one canister and functions completely independent from any other VVM.

The VVM provides for storage of canisters in a vertical configuration inside a subterranean cylindrical cavity entirely below the top-of-the-grade (TOG) of the facility. The canister Storage Cavity is defined by the Cavity Enclosure Container (CEC) consisting of the Container Shell integrally welded to the Bottom Plate. The top of the Container Shell is stiffened by the

Container Flange (a ring shaped flange), which is also integrally welded. All of the constituent parts of the CEC are made of thick low carbon steel plate. In its installed configuration the CEC is interfaced by the subgrade for most of its height except for the top region where it is surrounded by the Top Reinforced Concrete Pad.

The Top Reinforced Concrete Pad is configured to surround the external surface of the Container Shell and provide the riding surface for the cask transporter. The Top Reinforced Concrete Pad adjacent to the Container shell is overlapped by the Container Flange as illustrated in Figure 2.

Corrosion mitigation measures commensurate with site-specific conditions are implemented on below-grade external surfaces of the CEC. A corrosion allowance (metal wastage) equal to 1/8" on the external surfaces of the VVM in contact with the subgrade is nevertheless assumed in the structural evaluation. All external and internal surfaces of the VVM are coated or lined. The top surfaces of the canister Bearing Pads are equipped with stainless steel liners (or other appropriate barrier) so that the canister is not resting directly on carbon steel components.

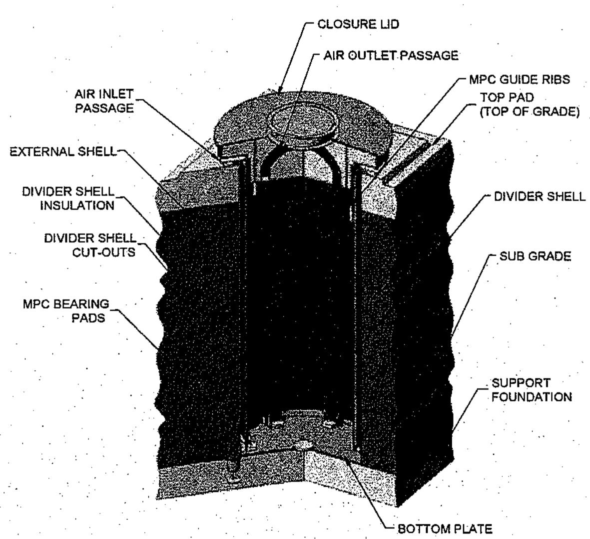

Figure 2. Anatomy of a HI-STORM 100U VVM

With the Closure Lid removed, the CEC is a closed bottom, open top, thick walled cylindrical vessel that has no penetrations or openings. Thus, ground water has no path for intrusion into the interior space of the canister storage cavity.

The canister Bearing Pads and the Divider Shell, two parts internal to the CEC, are important to the VVM's thermal performance. The Divider Shell, as its name implies, is a vertical cylindrical shell concentrically situated in the CEC. The Divider Shell creates an outer annular coolant air or intake plenum and an inner annular coolant air space around the canister. The bottom end of the Divider Shell has cutouts to enable incoming air streaming down the intake plenum to enter the inner coolant air space from around the circumference of the Divider Shell in a symmetric manner (Figure 3). The Bearing Pads (Figure 3) provide for a Bottom Plenum underneath the canister for access of coolant air. The cutouts in the Divider Shell are sufficiently tall to ensure that if the cavity were to be filled with water, the bottom region of the canister would be submerged for several inches before the water level reaches the top edge of the cutouts. This design feature is important to ensure uncompromised thermal performance of the system under any conceivable accidental flooding of the cavity by any means whatsoever. The Divider Shell is not attached to the CEC to permit convenient removal for decommissioning, for unplanned in-service maintenance, or for any other unforeseeable reason.

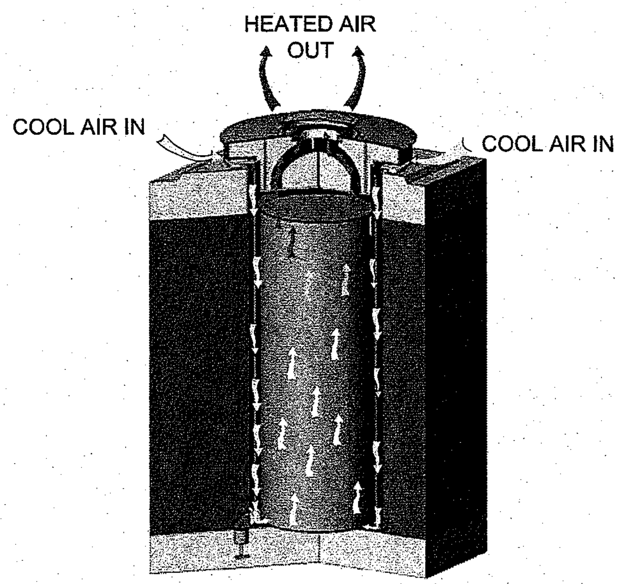

Figure 3. Ventilation Action in the HI-STORM 100U VVM

In addition to the lateral restraints at the bottom, the Divider Shell is also restrained against lateral movement at the top by the cylindrical protrusion in the Closure Lid. In addition, the Divider Shell is equipped with Upper and Lower canister Guides. The Upper Canister Guides are radially symmetric rib-like components located at the elevation of the canister's top lid. The Upper Canister Guides serve to guide the canister down to the Lower Canister Guides and Canister Bearing Pads during the canister's lowering operation, as well as to limit the canister's lateral movement during an earthquake event to a fraction of an inch.

Finally, the Closure Lid shown in Figures 2 and 3 completes the physical embodiment to the VVM. The Closure Lid is a steel structure filled with shielding concrete. The design of the top lid fulfills the following principal performance objectives:

i. Both the inlet and outlet air passages are located in the Closure Lid and therefore there are no lateral radiation leakage paths during the canister lowering or raising operation.
ii. Both inlet and outlet passages are radially symmetric so that the air cooling action in the system is not affected by the change in the horizontal direction of the wind.

iii. By locating the air inlet at the periphery of the lid and outlet at its top central axis, mixing of entering and exiting air streams is essentially eliminated.

iv. The inlet and outlet passages are made of "formed and flued" heads (i.e., surfaces of revolution) that serve three major design objectives as noted below.

   a. The curved passages eliminate any direct line of sight to the canister storage space and serve as an effective means to scatter the photons streaming from the stored fuel.

   b. The curved steel plates significantly increase the load bearing capacity of the Closure Lid much in the manner a curved beam exhibits considerably greater lateral load bearing capacity in comparison to its straight counterpart. This design feature is a valuable attribute if a beyond-the-design basis impact scenarios involving a large and energetic missile needs to be evaluated for a particular site.

   c. The curved passages, as is well known in classical hydraulics, provide for minimum loss of pressure in the coolant air stream, resulting in a more vigorous ventilation action.

v. The Closure Lid rests on the Container Flange. The Container Flange/Closure Lid interface also features a weather seal or gasket to preclude foreign material intrusion.

vi. The top surface of the Closure Lid is also curved and extended beyond the air inlet perimeter to efficiently drain off rainwater.

vii. The Container Flange restrains the Closure Lid against horizontal movement, during a Design Basis Earthquake event or a tornado missile strike.

viii. Because the inlet opening extends around the circumference of the Closure Lid, the hydraulic resistance to the incoming airflow, a common limitation in ventilated modules, is minimized. A similar airflow resistance minimization facility is built into the pathway for the exiting air. A circumferentially circumscribing vent opening is also quite obviously less apt to be completely blocked under even a most extreme environmental phenomena involving substantial quantities of debris.

ix. All inlet and outlet air passages are equipped with screens, as in the aboveground HI-STORM overpacks, to prevent debris, insects, and small animals from entering the VVM. The screen openings size and total perforation area are selected on a site-specific basis to minimize the resistance to the flow of the ventilation air while providing a reliable physical barrier against foreign objects.

x. The Closure Lid is intentionally made substantially larger in diameter than the Divider Shell in the CEC and the canister is positioned to be at a significant vertical depth below the top of the Container Flange. These geometric provisions ensure that the Closure Lid will not fall into the canister storage cavity space and strike the canister if it were accidentally dropped during its handling.

All canister types certified for storage in the aboveground overpacks can be stored in the VVM. The chief distinguishing features of the VVM are its low profile and subterranean configuration. The Container Shell is buried in the Top Reinforced Concrete Pad and subgrade for its entire height, resulting in virtually a complete blockage of laterally emanating radiation from the stored fuel. In summary, the notable design and operational features of the HI-STORM 100U VVM are:

i. The canister is supported on canister Bearing Pads to provide an inlet air plenum at the bottom of the storage cavity (Figure 2). The bottom of the canister, however, will be in contact with water if the cutouts at the bottom of the Divider Shell were to be filled with water cutting off feed air. Analyses show that, as long as the canister is wetted with water, the peak cladding temperature of the stored spent fuel will not exceed the regulatory off-normal condition temperature limit. Thus, the VVM configuration provides a built-in protection against flood events.

ii. Tipover of the canister in storage is not possible.

iii. Although the modules may be closely spaced, as illustrated in Figure 1, the design permits any canister located in any cavity to be independently accessed and retrieved using a HI-TRAC transfer cask.

iv. A cask transporter typical of those used in numerous Holtec dry storage sites for on-site transport of loaded HI-TRACs and HI-STORMs can provide the means to deliver the loaded HI-TRAC to the HI-STORM 100U VVM and to carry out the canister lowering operation. The same cask transporter can also be used to remove a canister from storage and place it in a recipient HI-TRAC transfer cask.

v. To exploit the biological shielding provided by the surrounding soil subgrade, the canister is entirely situated well below the top-of-grade level. The open plenum above the canister also acts to boost the ventilation action of the coolant air.

vi. The VVM, because of its underground configuration, does not have to contend with amplified soil-structure interaction effects that magnify the free-field acceleration and potentially challenge the stability of an aboveground freestanding overpack. Likewise, large natural hydrological force events such as tsunamis are not a concern for the VVM.

vii. Removal of water from the bottom of the storage cavity can be carried out by the simple expedient use of a flexible hose inserted through either the inlet or the outlet passageway.

viii. It should be recognized that the depth of the canister Storage cavity determines the height of the hot air column in the annular region during the system's operation. Therefore, deepening the cavity has the beneficial effect of increasing the quantity of the ventilation air and, thus, enhancing the rate of heat rejection from the stored canister. Further, lowering the canister in the canister Storage cavity will increase the subterranean depth of the radiation source, making the site boundary dose even more miniscule.

As can be readily deduced from the above description of the VVM, the canister storage cavity (consisting of the Container Shell and Bottom Plate) is at near ambient temperature during normal operations. The only portions of the VVM in contact with heated ventilation air are the Divider Shell and the domed annular outlet in the Closure Lid, neither of which is in contact with the subgrade soil.

Finally, the physical hardening of the VVM against impulsive and impactive loadings is a major consideration in the embodiment of the HI-STORM 100U VVM. The low physical profile of the VVM reduces the probability of impact from a missile or a projectile. In addition, to impute maximum margin against extreme environmental phenomena loads, the Closure Lid is a METCON® (metal/concrete) structure engineered to possess considerably greater strength reserve than that required to prevent design basis missiles from penetrating into the canister storage cavity. Another design consideration is protection against intrusion of rainwater and other liquid matter into the canister storage cavity. In contrast to typical ventilated modules, the VVM air passages are elevated above the Top-of-the-Grade, providing a physical barrier against the intrusion of any accumulating pool of fluid (including combustibles) on the storage facility surfaces into the module cavity. A significantly enhanced level of protection against incident missiles and an improved barrier against ingress of rainwater or spilled fluids into the module cavity space, and a design that is ideally configured for a flood event, are among the key distinguishing features of the HI-STORM 100U VVM.

BENEFITS AND SHORTCOMINGS OF THE UNDERGROUND STORAGE SYSTEM

In the following, a resume of the merits and shortcomings of the HI-STORM 100U is provided.

Merits

1. Stored fuel is virtually inaccessible to attack from an aircraft or a conventional missile.
2. Extremely robust against a direct hit from a projectile of any kind, making release of radiological matter virtually impossible.
3. Flood does not challenge the thermal performance of the storage system.
4. Natural hazards such as hurricanes, tsunami, or tornados do not challenge the integrity of the storage system.
5. Because the VVM storage cavity is a closed bottom container, combustion of flammable material placed in the cavity cannot be sustained.
6. Underground placement of fuel renders the dose released from the storage cavities to negligible values.
7. Less occupational dose in loading the canister into the storage cavity because of improved human factors and work durations.
8. Loading and shipment of canister out of storage is convenient and efficient. The Part 50 infrastructure (crane, truck bay, etc.) is not needed to package and ship the loaded canisters.
9. Surveillance of the storage facility to inspect the duct openings is a physically trivial effort because the ducts are near ground level and thus are readily visible by a person from any location around the storage facility.
10. A "100U" storage facility is essentially invulnerable to earthquake even under soil liquefaction scenarios.

Demerits

1. Although an underground HI-STORM storage facility will be affected by flood only after floodwaters exceed 8" in height over the storage facility pad surface, cleaning the storage of debris washed in by floodwater will take more work than in an aboveground system.
2. Substantial on-site construction work is required, in contrast to the aboveground HI-STORM modules that require little in the way of on-site resources (up to four aboveground HI-STORMs have been filled with concrete in one day).
3. Sites with a high water table will require design measures to keep the VVMs from being permanently immersed in wet subgrade. A cathodic protection system is required in the system FSAR to all sites except those with non-aggressive subgrades.
4. Unlike the aboveground HI-STORM 100S overpack, which is made of steel, and hence can in principle be transported from one site to another for use, the HI-STORM 100U (save for its closure lid) is immovable.
5. Unlike the aboveground overpack that can be loaded in the nuclear plant's truck bay or at the storage facility, the 100U VVM must be loaded at the storage facility.

CLOSURE

To summarize, the underground HI-STORM 100U module provides the most desirable storage configuration if the user:

i. wishes to have vanishingly small site boundary dose, or
ii. has flood or concerns, or
iii. has a small land area available for installing the facility, or
iv. wishes to significantly reduce the probability of a strike from a crashing aircraft (the kind of threat admitted by the ASLB for the Skull Valley Away-From-Reactor Storage Facility or similar sources of threat, or
v. wishes to have the ultimate degree of protection against radiological release if struck by a missile or a projectile, or
vi. has the facility located in geological terrain prone to liquefaction and/or high seismic motions, or
vii. wishes to have a visually inconspicuous storage system.

If any of the above reasons is deemed to be important, then HI-STORM 100U is a meritorious system for such a site.

The HI-STORM 100U design described in this paper is one of several designs that are either patented [4] or are in the process of being patented under U.S. and international patent laws. However, the design described herein is the only one that is in the USNRC's licensing queue at this time.

Due to constraints of available space, a reader wishing for an in-depth analysis of a system's performance under the various scenarios (such as earthquakes) is referred to the system FSAR [1].

REFERENCES

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[6] "Ventilated Vertical Overpack", U.S. Patent No. 6,718,000, by K.P. Singh, dated April 6, 2004.