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NUHOMS® System for Storage and Transportation of VVER Fuel

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ABSTRACT

Orano TN (TN) has been awarded contracts for the supply of China's first spent fuel dry storage facilities in Tianwan Nuclear Power Plant (NPP) with VVER-1000 fuel assemblies and Daya Bay NPP with PWR fuel assemblies. TN's NUHOMS® System is a proven and widely used spent fuel dry storage technology and has been licensed by the US Nuclear Regulatory Commission (USNRC) for more than 35 years and implemented in the United States and Armenia for spent fuel dry storage of various fuel types including PWR, BWR, and VVER-440. NUHOMS® System is adapted to meet site specific needs from Tianwan NPP and NUHOMS® 31VTH system is ideally suited for the Tianwan site and its VVER-1000 spent fuel. This system has been approved by the China National Nuclear Safety Administration (NNSA) for use at Tianwan.

This paper will present the design and development of NUHOMS® 31VTH, which is a dual purpose storage and transportation canister and can store 31 VVER-1000 type fuel assemblies, providing criticality control, containment, and heat removal. As China begins implementing dry storage, it is simultaneously developing the governing regulations. In the meantime, the licensing application relies heavily on the USNRC model. There are some differences of emphasis, which are explored in this paper. With this project, the NUHOMS® system continues to demonstrate its adaptability to different fuel types, site conditions, environmental conditions, and regulatory requirements.

INTRODUCTION

NUHOMS was the first system to place nuclear fuel in a canister with a welded closure, and to store the dry canister inside a concrete overpack. First loaded in 1989 at the H.B. Robinson nuclear generating station[1], NUHOMS remains to this day the only system to offer horizontal storage. By transferring the loaded canister horizontally from the power plant to the dry storage facility, and storing the canister horizontally in the concrete module, the system eliminates the need to suspend an unprotected canister at a height of about 5 meters to lower it into a vertical concrete silo. By placing the bunker-like modules in contact with one-another, the NUHOMS system provides shielding 5 to 10 times better than competing vertical concrete or metal cask systems.

These advantages helped TN Americas win a contract for delivery of NUHOMS storage systems to the Daya Bay and Tianwan nuclear power plants in China. While Daya Bay was able to use a standard TN product for storage of its 17x17 PWR fuel, the contract with Tianwan necessitated the development of a new product for its VVER-1000 fuel, and special accommodations for the operations interface at a VVER plant. The NUHOMS system had once before been used for VVER-400 fuel at Armenia's ANNP since 2000[2]. The VVER-1000 storage canister would need to address the demands of the market in 2017: high capacity and high decay heat storage. In addition, to simplify eventual transport to a recycling plant, the criticality safety for 5% enriched fuel would have to be accomplished using a combination of fixed neutron absorbers and burnup credit, with no credit allowed for the spent fuel pool's dissolved boron.

PHYSICAL DESIGN OF THE 31VTH BASKET

The first constraint that needed to be addressed in the design was due to the small diameter of the VVER's cask loading pit. The transfer cask that carries the DSC from the loading pit to the concrete storage module could not be any larger than TN's OS200 model, that is, the canister would be limited to 1772 mm outside diameter. Further constraining the space available were the specified fuel compartment inside dimension of 245 mm and 340 mm clear diameter for the fuel handling machine as shown in Figure 1. The result of these constraints was that the space between fuel compartments would be severely limited if the canister was to hold the desired 31 fuel assemblies.

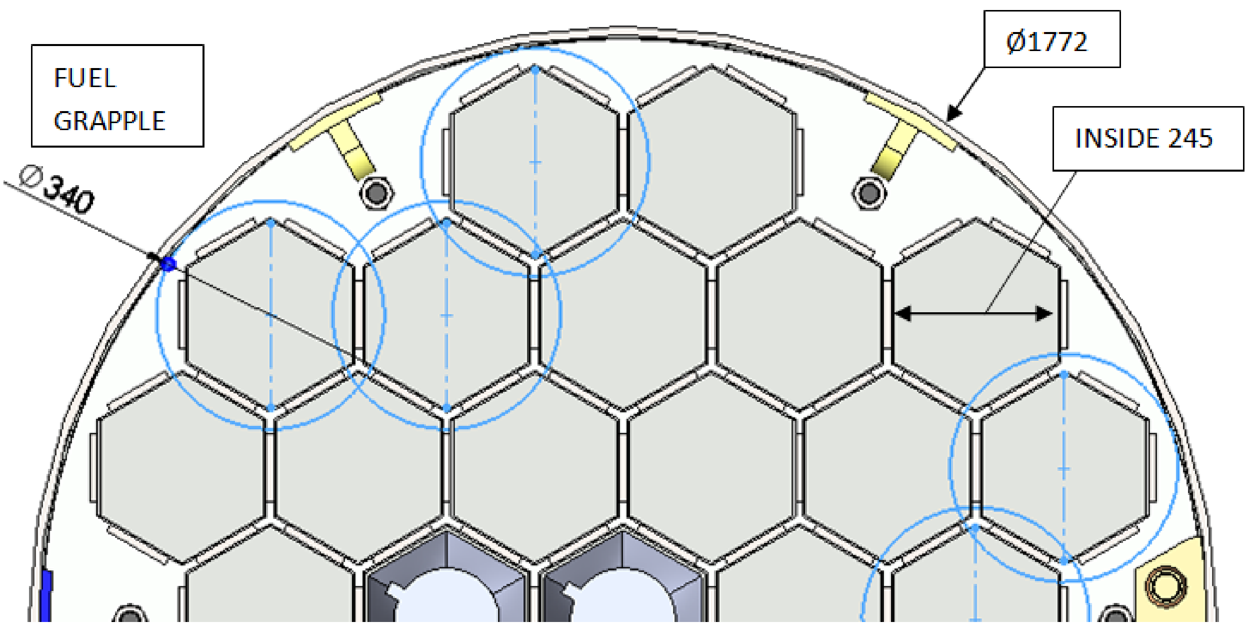

Figure 1: Layout for 31VTH basket

The challenge now was to fit components for structural support, heat transfer, and criticality control within this tight space. With square fuel compartments, there are options to build the basket from interlocking plates with or without tubes. This cannot be done with hexagonal close packing. TN chose a tube-and-disc construction. Such designs have been used for a long time, but they have several disadvantages to be overcome. They can be expensive due to the machining of the holes in the discs and the waste of the cut out material. They are generally poor for conducting heat from the fuel to the canister shell. Sometimes this is overcome by placing machined aluminum discs between the steel structural discs, but this only compounds the first problem. TN addressed these challenges by using high-strength low alloy steel (SA-517) for the structural discs to minimize the number of discs and their material cost. In addition to its high strength, the nickel-bearing alloys under this specification can be supplied to meet the impact test requirements of ASME NG-2330[3] for a minimum service temperature of -40°C required by IAEA transport regulation SSR-6[4]. The fuel load was transferred to these discs via stainless steel type 304 fuel compartments. To provide heat transfer paths and to secure the neutron absorber, TN surrounded the six sides of each fuel compartment with a sheet of aluminum/B4C metal matrix composite (MMC) surrounded by a close-fitting hexagonal aluminum sleeve. At the basket perimeter, solid aluminum blocks completed the heat transfer path to the shell. The MMC, aluminum sleeve, and aluminum blocks were all captured between the structural discs, while the stainless tubes are continuous through the discs. An exploded view of the basket is shown in Figure 2, and the complete assembly of basket and shell is shown in Figure 3.

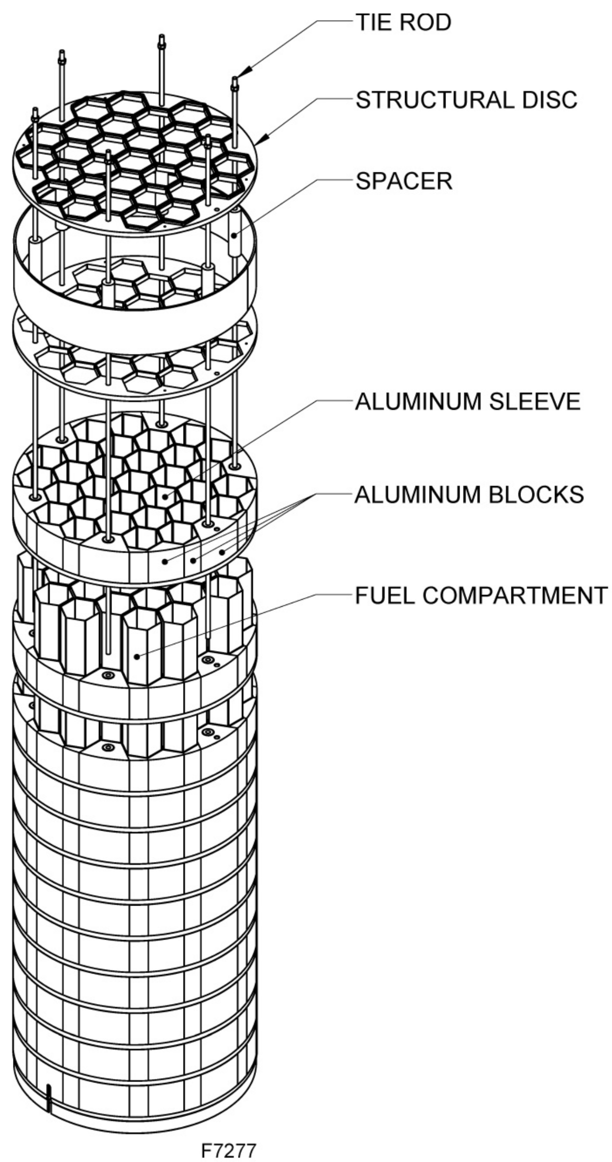

Figure 2
Exploded view of the basket assembly

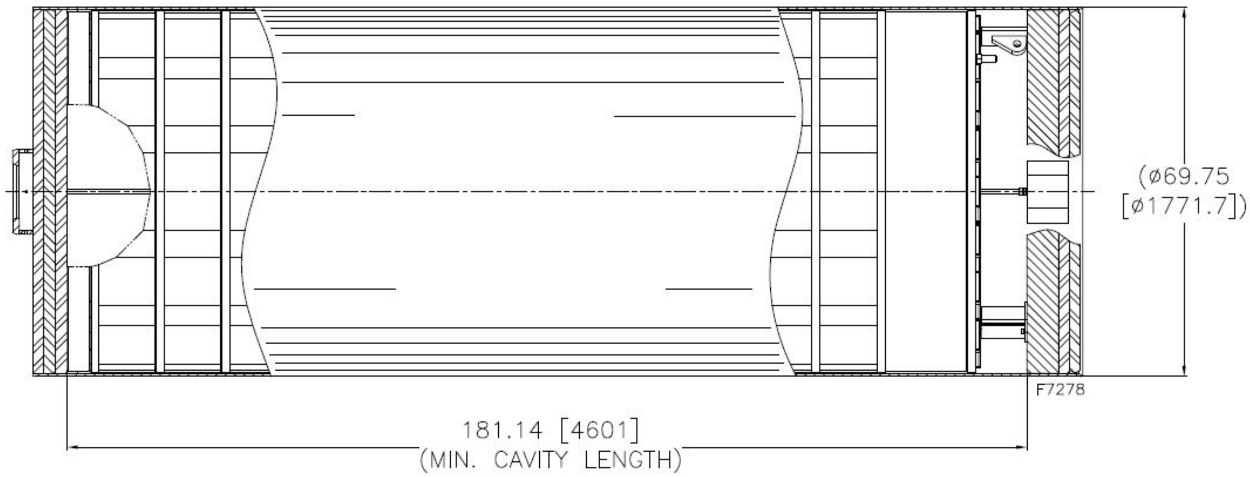

Figure 3
Complete 31VTH Canister Assembly

DESIGN ANALYSIS

The 31VTH canister shell and end plates were the same as the existing 32PTH1 canister, with minor exceptions, and the weight of the 31VTH contents was smaller than the design basis for the 32PTH1, so very little analysis of the shell was required. The major new analyses were for the structural, thermal, and criticality functions of the basket.

The stress criteria for the 31VTH's major structural components – discs, tubes, tie rods, and spacers - were taken from ASME NG-3200 for normal conditions and Section III Appendix F for accident conditions. The aluminum sleeves and neutron absorber plates were not modeled, but their weight was added to the stainless steel tubes. For side loads, the perimeter aluminum blocks were included, and the fuel was modeled as a pressure load with no credit for the fuel assembly stiffness.

The limiting conditions for the structural analysis of the basket were impact accelerations of 75g on the side and the end. These bound both a 2 m drop of the transfer cask without impact limiters and the 9 m hypothetical accident condition drop in a transport cask with impact limiters. Although licensing for transport was not a part of the project, the canister is designed to be in principle transportable in a transport cask such as TN's MP197-HB. The accident condition structural analyses, performed with LS-DYNA[5], demonstrated that all stresses remained below allowables at 75g, and that the structure was stable against buckling to 85g. Multiple rotational orientations were investigated.

To achieve the high thermal capacity of 35.25 kW total, the basket was divided into three zones as shown in Figure 4, where zone 1 has the lowest decay heat per fuel assembly, and zone 3 the highest. The surface temperatures of the canister were determined by a CFD analysis using ANSYS FLUENT[6], with the canister inside the transfer cask and the concrete storage module. These surface temperatures were then used as the boundary conditions for an ANSYS[7] FEA model of the canister shell, basket, and fuel. This analysis demonstrates that the fuel cladding remains below the normal condition temperature limit of 400°C, and provides the material temperatures for the structural analysis. The thermal analysis internal to the canister relies only on conduction and radiation. Because it does not require internal convection, the canister can be backfilled at a low pressure of helium, less than 20 kPa.

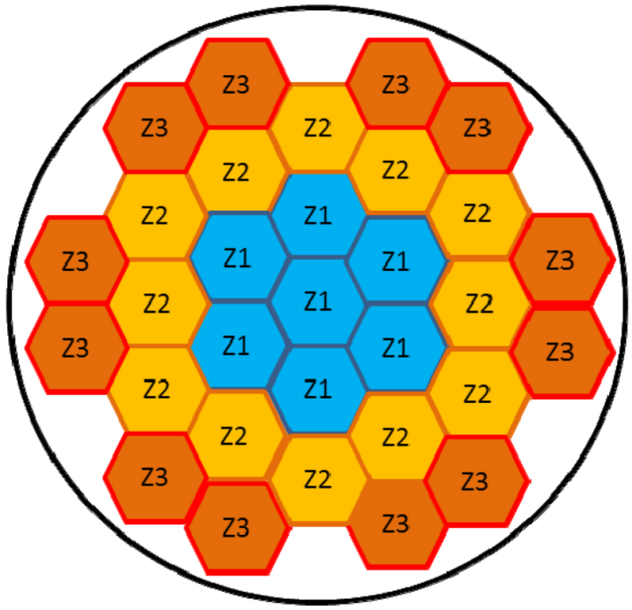

Figure 4
Thermal Zones in the 31VTH Basket

The canister includes shield discs top and bottom, but radial shielding depends on the transfer cask and the concrete module. Although the thermal arrangement with the hottest fuel on the perimeter of the basket is not optimal for dose rate reduction, the calculated average dose rate at the surface of the concrete storage modules was below 0.01 mSv/hr at the rear and end walls, and less than 0.04 mSv/hr on the front face, which includes the contribution from the inlet vents. With supplementary shielding barriers at the inlet vents, the dose rate at the storage area boundary, only 2 m from the storage array, was below 1 μSv/hr.

The criticality analysis is based on full moderation by pure water, with burnup credit based on US NRC Interim Staff Guidance ISG-8 revision 3[8]. The burnup credit analysis considered twelve actinides and sixteen fission products. The depletion calculations were performed with ORIGEN-ARP[9], and the criticality calculation with KENO-VI[9]. K_{eff} was less than 0.95 for normal conditions, including all bias and uncertainty, and the most reactive configuration of fuel and basket. Because the structural analysis showed that there was no plastic deformation of the basket or fuel in the accident conditions, the normal condition criticality calculations covered accident conditions as well. Figure 5 shows the resulting loading curve.

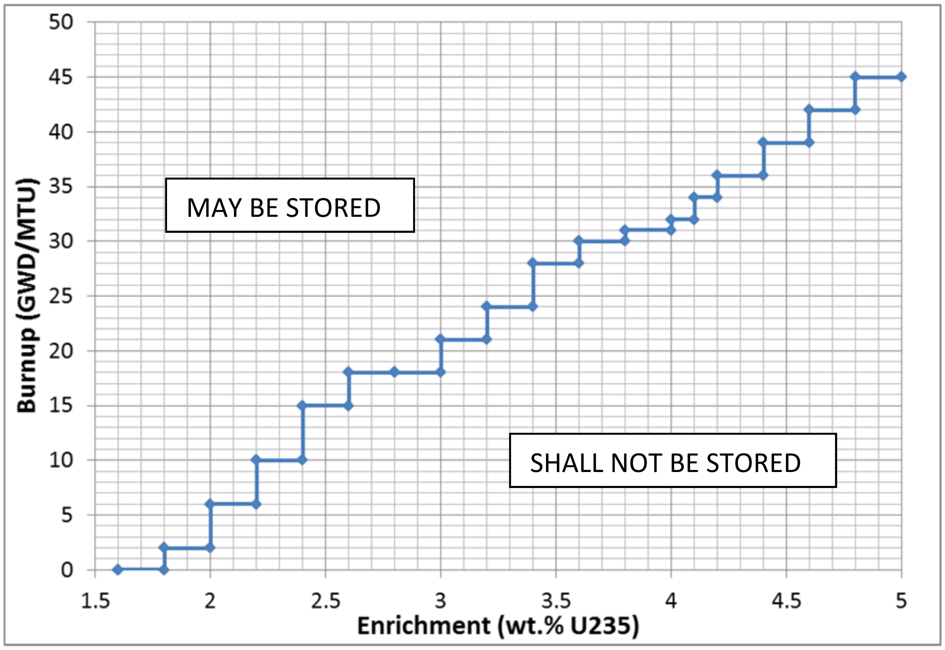

Figure 5
Burnup-credit Loading Curve

OPERATIONAL DESIGN

Several features of the VVER plant interface presented challenges for a system designed primarily for the light water reactors in the US. These features include the fuel handling machine, the small diameter loading pit, and the transfer into and out of containment on a rail wagon 20m above ground level.

The clear diameter needed for the fuel grapple has been mentioned above. In addition, the fuel assemblies must stick out of the basket sufficiently for the grapple to engage them, but the grapple must also contact the top of the basket to disengage the fuel. This results in a large gap between the basket and the lid. Heavy restraints were mounted under the lid at the location of the tie rods to prevent the basket from shifting under accident loads.

Furthermore, the fuel machine is incapable of rotation, and therefore the basket must be accurately aligned with the pool rack. To accomplish this alignment, an adapter was mounted to the bottom of the OS200 transfer cask to mate with the keyed seat in the loading pit. To adapt to the small diameter of the loading pit, the transfer cask radial neutron shield was cut back in the vicinity of the lifting and rotating trunnions, and the trunnions were moved inward.

The loaded cask is transferred out of containment with the bottom trunnions clamped to a rail wagon. The OS200 transfer cask did not fit into the rail wagon and clamps, which were designed for a Russian transport cask. To make this work with minimum modification, TN designed seismically-qualified clamps that could replace the hinged upper portion of the existing clamps. Thus, the newly designed clamps could be installed without any permanent modification of the wagon, as shown in Figure 6.

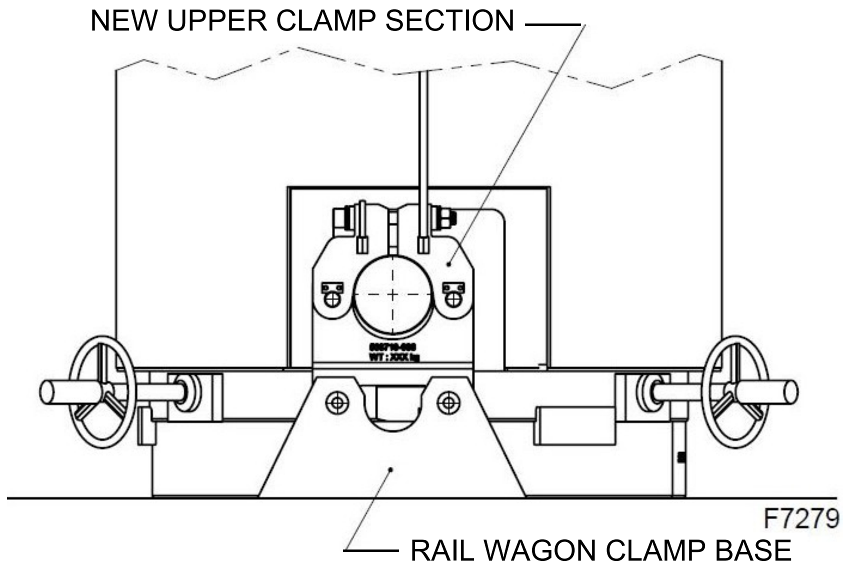

Figure 6
Rail Wagon Clamp Adaptation for the OS200 Transfer Cask

FABRICATION EXPERIENCE

One of the advantages of the tube-and-disc basket construction is that it is mechanically assembled. The only welding is on the long seams of the stainless steel fuel compartments. The aluminum sleeves are at the margins of extrusion capability, but they can also be formed and welded. Given the tight space constraints, the tubes and sleeves had to push the limits of economical forming tolerances, and the structural discs similarly pushed the limits of economical machining tolerances. To confirm the feasibility of construction before the first unit, a half-length prototype was constructed. The prototype resulted in only minor changes in the dimensional inspection requirements. The first complete baskets have been successfully constructed, as shown in Figure 7.

Figure 7
First Unit Fabrication of the 31VTH Basket, 95% Complete

CONCLUSIONS

In recent years, the major design challenge for storage and transport systems has been the user demand for higher capacity, higher decay heat, higher enrichment and burnup, and lower dose rates. The development of the NUHOMS 31VTH canister for VVER 1000 fuel was no exception. In this case, the challenges were overcome by dusting off an older design concept, the tube and disc basket, and updating it with new features and materials to improve its performance.

Another challenge arises when the interfaces at a plant are designed with a specific transport cask in mind, in this case a Russian TUK. Normally, competitive pressures do not allow for complete redesign of an alternate system to accommodate these interfaces. In this case, for example, complete redesign of the OS200 transfer cask would likely have priced TN out of the competition. Thus, the OS200 had to be adapted by minimum design changes, and by adaptive add-ons to either the cask or to the plant equipment.

A third challenge can arise when designing a product for a new nuclear regulatory environment. As China develops its own general regulations for dry storage of used fuel, it is in the meantime treating dry storage as a modification of each plant license, using the US regulation 10 CFR 72[10] and the associated NRC standard review plans as guidance. The differences were mainly in the requirements for criticality safety with pure water moderation and for lower dose rates, but these were not insuperable obstacles.

ACKNOWLEDGMENTS

Figure 7 courtesy of Shanghai Apollo Machinery Co., Ltd

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