Innovative Solutions for Loading Smaller Standardized Dry Storage Canister Systems for Used Nuclear Fuel - 16232

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ABSTRACT

An integrated team lead by Energy*Solutions* has developed and evaluated design concepts and loading processes for standardized transportation, aging and disposal (STAD) canister systems for the dry storage of United States (US) commercial used nuclear fuel (UNF). These STADs would be smaller than the Dual Purpose Canisters (DPCs) currently in use for storage and transportation of UNF at the nuclear power plant (NPP) sites in the US, so it was necessary to study the operational requirements and impacts related to their implementation at the NPPs and develop innovative approaches to mitigate these impacts. This work was funded by the US Department of Energy (DOE) to support the DOE in evaluating the option of using standardized canister systems for storage, transport, and disposal of US commercial UNF as part of an integrated waste management system. The NPP utilities are currently placing UNF into increasingly large DPCs because this reduces loading times and associated worker dose uptake. However, whether large DPCs may be able to be directly disposed is not known at this time, and will depend in part on future geologic disposal concepts and the DPC heat content. The use of STAD canisters rather than DPCs at the NPP sites and/or at an interim storage facility could avoid a potential need to repackage the UNF for disposal but, to make STAD canisters attractive for use, ways need to be found to fill and seal them efficiently from an operational perspective.

This paper describes the generic design for a small STAD canister system, the loading processes and process improvements that were identified for the small, medium and large STAD canister sizes, the methodology for, and results from, the assessment of the performance of the loading processes, and the practicality of the results versus NPP operating experience. The work that this paper reports thus reflects research and development efforts to explore technical concepts that could support future decision-making by DOE.

INTRODUCTION

In early 2010 the Blue Ribbon Commission on America's Nuclear Future (BRC) was chartered by the President to recommend a new strategy for managing the back end of the nuclear fuel cycle. In January 2012 the BRC published its final report [1], which contains several recommendations including that prompt efforts should be made to develop consolidated interim storage facilities for used nuclear fuel (UNF)[1] , and that similar efforts should be made to develop one or more geologic disposal facilities. Consolidated storage would allow the consolidation of the UNF to one or more sites in the US from its current storage locations at the 61 operating commercial nuclear power plant (NPP) sites housing 99 reactors, 13 shutdown commercial sites and the non-NPP Morris IL site. Some of the shutdown sites now have no infrastructure other than casks on a pad storing the UNF dry in canisters, while more recently shutdown sites still retain

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[1] The term "used nuclear fuel" is intended to be synonymous with the term "spent nuclear fuel" as used in the Nuclear Waste Policy Act of 1982, as amended, and the Standard Contract that DOE has in place with nuclear utilities (10 CFR Part 961).

water-filled pools for wet storage of their UNF. Some operating NPP sites have both wet and dry storage of their UNF, others have solely pool storage, but will establish dry storage shortly because their pools are becoming full. As the NPP pools fill up and the utilities move to dry storage, there is an incentive for them to use the largest dry storage canisters that can be licensed because these are efficient to handle and fill. Such large canisters may not, however, be compatible with all future geologic repositories because of their relatively high heat output, and this may lead in the future to the need to repackage UNF into smaller canisters. There is thus an incentive to explore whether smaller canisters can be designed and handled in ways that approach the efficiency of the large ones, so they can be used straight away, reducing the potential need for future repackaging.

In response to the BRC's recommendations, DOE issued the Administration's Strategy, published in January 2013 [2]. This document articulated that, with appropriate authorizations from Congress, the Administration plans to implement a program over the next 10 years that:

- Sites, designs and licenses, constructs and begins operation of a pilot interim storage facility (PISF) by 2021, with an initial focus on accepting the UNF from the shutdown NPP sites where it is solely in dry storage;
- Advances toward the siting and licensing of a larger consolidated interim storage facility (CISF) to be available by 2025 that will have sufficient capacity to provide flexibility in the waste management system and that allows for acceptance of enough UNF to reduce expected government liabilities;
- Makes demonstrable progress on the siting and characterization of geologic repository sites so as to facilitate the availability of a geologic repository by 2048; with a goal of having the repository sited by 2026, and the site characterized with the repository designed and licensed, by 2042.

To support its preliminary planning efforts, DOE has placed study tasks with several industrial teams to study various technical options associated with the handling and movement of UNF from the NPP sites to a PISF or CISF. These have included possible canisterization[2] of the UNF at the NPP sites into triple-purpose (standardized transport, aging, and disposal - STAD) canisters, using different capacity STAD canisters to cover a broad range of disposal concepts, transport of both "bare" and canistered UNF to a CISF, and the development of CISF concepts. Energy*Solutions* has lead teams working on several of these study tasks, including Concepts for Consolidated UNF Storage [3], the Feasibility of Standardized Transportation, Aging and Disposal Canisters (STADs) for UNF [4], Consolidated Storage and Standardized Storage Canisters [5] and the Transport and Dry Storage of Used Nuclear Fuel [6].

This paper describes work that EnergySolutions and its team partners NAC International, Exelon Nuclear Partners, Talisman International, Booz Allen Hamilton and Petersen Inc. have carried out via two separate, but complementary, studies to develop a generic design for a small STAD canister system, and to develop equipment and operational procedures that will enable the handling and loading of small, medium and large STADs in ways that approach the efficiency of the large dry storage canisters currently being used by the NPP utilities in the US. This paper thus reflects research and development

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[2] This is a technical paper that does not cover the contractual limitations under the "Standard Contract" that DOE has in place with nuclear utilities (10CFR Part 961). Under the Standard Contract, DOE is obligated to accept only bare UNF. Acceptance of canistered UNF would require a mutual agreement to modify the contract.

efforts by the Team to explore technical concepts which could support future decision making by DOE. No inferences should be drawn from this paper regarding future actions by DOE.

USED NUCLEAR FUEL HANDLING AND STORAGE IN THE US

UNF is currently being discharged from the 99 nuclear reactors at approximately 2000 tons per year due to routine reactor refueling, and the total UNF currently stored at the NPP sites is now more than 74,000 tons. The UNF storage pools at the NPP sites in the US are currently becoming full and the NPP utilities are increasingly adopting dry storage in stainless steel canisters enclosed in concrete casks placed on pads or in concrete vaults, so as to free up pool space for the freshly discharged UNF. These canisters are designed for interim storage and transport only and are thus termed Dual Purpose Canisters (DPCs). The 2000 tons of “fresh” UNF that arises annually and has to go to pool storage, displaces an equal amount of older UNF annually into new dry storage. Currently 26wt% of the US’s UNF is in dry storage and 74wt% is in pool storage, with the dry storage amount now rising by 2000 tons per year.

There are clear incentives for the utilities to use the largest DPCs that they can get licensed, and currently canisters containing up to 37 PWR or 89 BWR fuel assemblies are coming into use. These large DPCs are efficient in use, reducing the total loading time for a given amount of UNF and thus also decreasing workforce radiation dose uptake. However, the relatively high heat output of such large canisters means that it is uncertain at this time whether they are suitable for direct disposal in a future geologic repository. This will depend in part on the future geologic disposal concepts and in particular on the heat removal properties of the surrounding geologic materials. If the large DPCs do indeed prove to be unsuitable for repository storage then a substantial repackaging of the UNF into smaller canisters will eventually be required.

One means of mitigating this issue, and thus avoiding the need for repackaging of at least some UNF, is the use of smaller Standardized Transport Aging and Disposal (STAD) canisters, designed so that their total heat output, even at the minimum 5 year out-of-reactor cooling of the UNF, is within the capacity of some or all possible geologic repository geologies. In a previous study that Energy*Solutions* and its team partners carried out for DOE [4] three such STAD sizes were identified and their conceptual designs completed. These STADs hold, respectively, 4PWR/9BWR, 12PWR/32BWR and 24PWR/68BWR UNF assemblies and were designated small, medium and large. However, these STADs are all smaller than the 37PWR/89BWR ones currently being used by the NPP utilities and will therefore potentially impose a longer loading time for a given amount of UNF. The study described in this paper was therefore funded by the DOE to see whether and how this drawback could be mitigated, so that smaller STADs could become more attractive for use by the NPP utilities.

Energy*Solutions* has worked with its team partners to develop STAD design concepts and innovative operational approaches to handling and filling the STADs. The overall objective of this study was to develop designs for STADs and operational methods for filling, closing and handling them that approach the handling efficiency of the large DPCs currently being used at the NPP sites, thus making the STADs more practicable and attractive to use.

STAD CANISTER SYSTEM DESIGN CONCEPTS

The small, medium and large STAD canister designs developed during our previous study [4] are shown in Figure 1. For the present study, the small and medium STAD designs were retained, but the large 24PWR/68BWR STAD was changed to one containing 21PWR or 44BWR assemblies. The 21PWR version of this large STAD is shown in Figure 2. This slightly smaller large STAD design was used for the present study so as to be consistent with the large STAD capacity identified by DOE for this study, based on results from other industry studies.

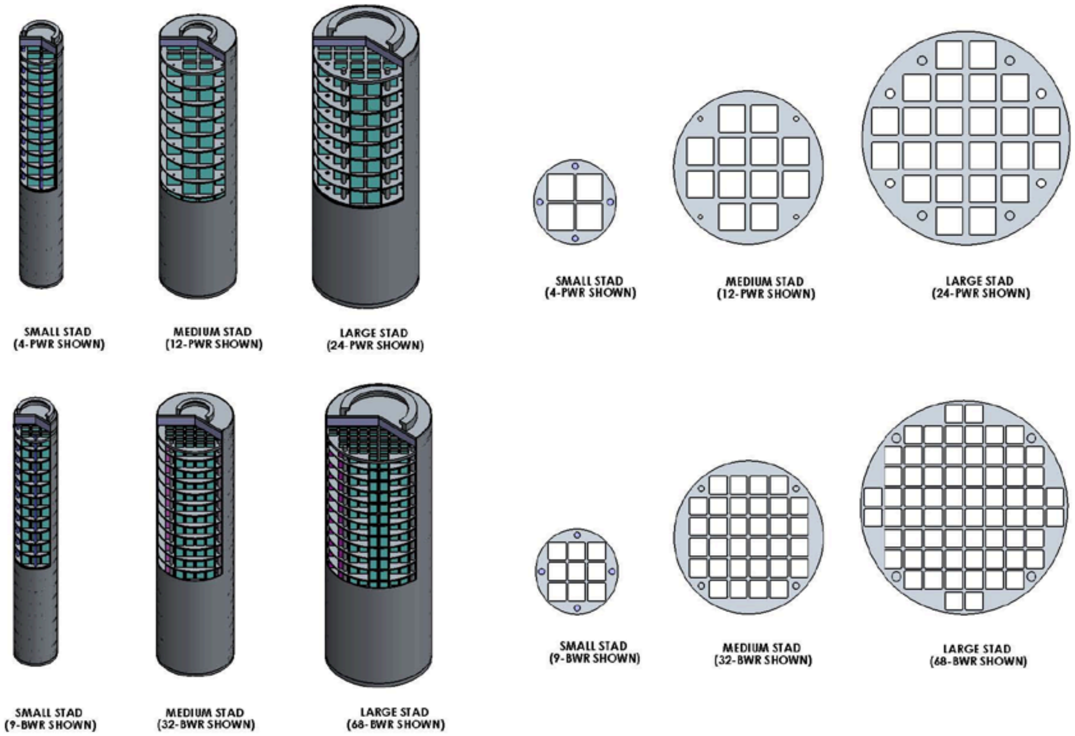


Figure 1: Small, Medium and Large STADs Developed During Prior Study

All of the STADs considered in the studies were based on a right circular cylinder canister, a design which is widely used in the UNF dry storage industry because it has many clear design advantages over non-circular shapes, such as inherent strength and dimensional stability for internal pressure loads. It was noted during the study that, in the case of the small STAD and considering loading multiple small STADs into a storage or transportation overpack, that utilizing STAD canisters with a square cross-section would allow more STAD canisters and hence more UNF assemblies to be loaded into an equivalent size of storage or transportation overpack. Scoping level structural analyses showed that such canisters could be designed to cope with the internal pressure loads; albeit with a shell wall thickness that would need to be doubled, increasing the overall weight. The unit costs for these non-circular STADs are expected to be higher than those of the right circular cylinder design, but these may be offset by overall savings due to fewer storage and transportation overpacks being required. Nevertheless, for this study square cross-section canisters were not pursued.

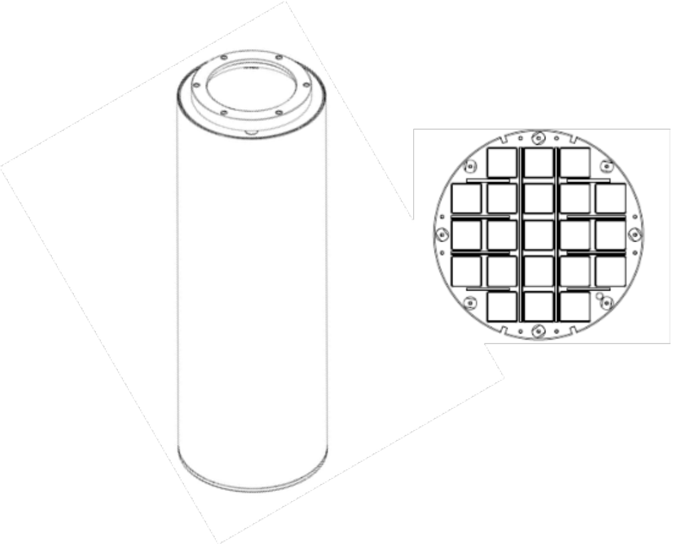


Figure 2: 21-PWR Large STAD Design used for this Study

STAD Canister Design Considerations

The STADs were designed to be loaded with UNF and seal welded at a reactor site, at a CISF, or at a repository and to be transportable by rail horizontally in a multi-canister overpack. They are capable of being stored in two configurations: (i) in a multi-canister overpack horizontally or vertically, and (ii) in a vault that can be above or below grade. All three sizes of STAD were initially designed to accept PWR and BWR fuel with burnup levels up to 80,000 MWd/metric ton uranium (MTU) and 70,000 MWd/MTU, respectively, and with initial U-235 enrichment levels of up to 5.0 wt% U-235. The STAD canisters were also designed to accommodate partial, damaged or Mixed Oxide (MOX) fuel assemblies, as well as intact PWR and BWR assemblies. Analyses were carried out of the STAD conceptual designs, for their structural, heat load, radiation dose and criticality control performance, and these showed that the designs were practicable, fabricable and licensable.

Development of Efficient Methods for Handling and Filling Small STADs

Because all of the STAD designs are smaller than the large DPCs currently being used by the NPP utilities, all would potentially take longer to load a given amount of UNF, and so the operations to fill and seal all three sizes were studied to identify how efficiency could be improved. The small STAD canister concept would be compatible with the widest variety of geologic disposal concepts including back-filled (enclosed) concepts and those which could accommodate less than 100 year out-of-reactor UNF cooling times, making it the most versatile and the most likely canister design to obviate a future repackaging exercise. However, it would be the most inefficient to fill. Because of this, methods of handling and filling small STADs in parallel were explored as a precursor to the study of filling and sealing operations for all three STAD sizes.

The small STAD conceptual design developed is shown in Figure 3. Two variants were developed, one for the 4-PWR and one for the 9-BWR STAD. Each variant comprises a shell assembly which is identical for both, with specific designs of internal basket for each variant as shown in Figure 1. The STAD canister shell assembly includes an initially open-top shell body that contains the internal basket assembly. In use, UNF would be loaded into the basket contained within the canister shell body in the reactor or CSIF pool, after which a shield plug would be placed into the top end of the shell body to provide radiation shielding for workers during the subsequent canister closure operations. The shell body includes an internal ring at the top end that is used to temporarily support the shield plug within the shell prior to welding the shield plug to the shell. The shell body assembly also includes a vent/siphon block and ports that are used to drain and dry the UNF and inside of the canister during loading operations. The shield plug has two holes through which the vent and siphon port tops fit. The STAD canister would then be removed from the pool, enclosed in a carrier and transfer cask system (see next section) to provide operator radiation shielding. A small amount of water would then be drained from the STAD canister cavity, the shield plug would be welded to the canister shell and a hydrostatic pressure test performed to confirm, in conjunction with non-destructive examination, the integrity of the weld.

Following full canister draining and drying operations, and filling the canister cavity with helium to a positive pressure, small circular covers would be welded over the vent and siphon port tops to complete the inner confinement boundary. The top plate assembly, which includes an integral lifting ring, would then be placed on the shield plug and welded to the canister shell, forming a second, redundant, seal boundary, as typically required for NRC licensing.

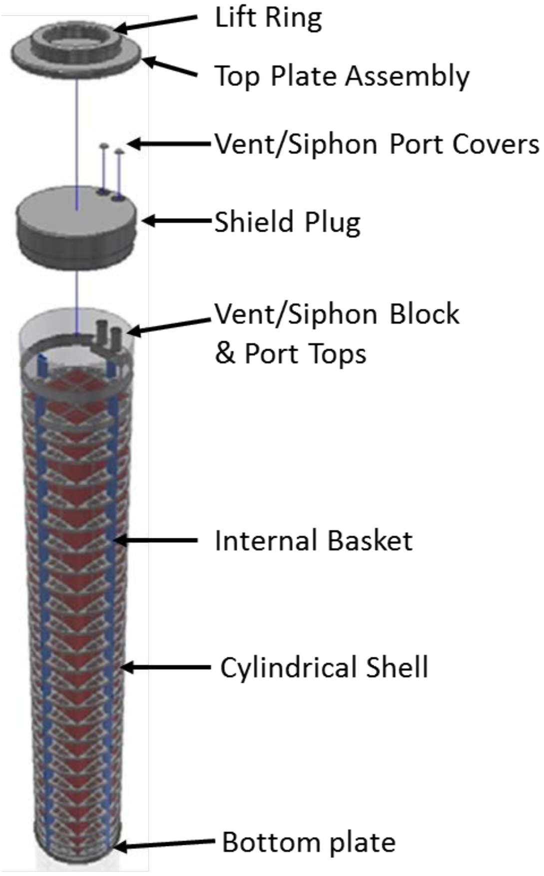


Figure 3: The Small STAD

Canister Carrier and Transfer System

The overall scheme for loading and transferring STAD canisters to either dry storage or a transport operation is shown in Figure 4. To enable the parallel handling of four small STADs, the canister transfer system utilizes an innovative “carrier” for four small STADs, shown in Figure 4 without STADs, and in Figure 5 with STADs and within a transport cask. The carrier locates and supports the four small STAD canisters during loading operations, transport conditions and storage conditions. Use of the carrier is designed to reduce the number of primary loading and handling operations and it also provides opportunities for parallel welding, non-destructive examination, and drying operations of STADs to be performed.

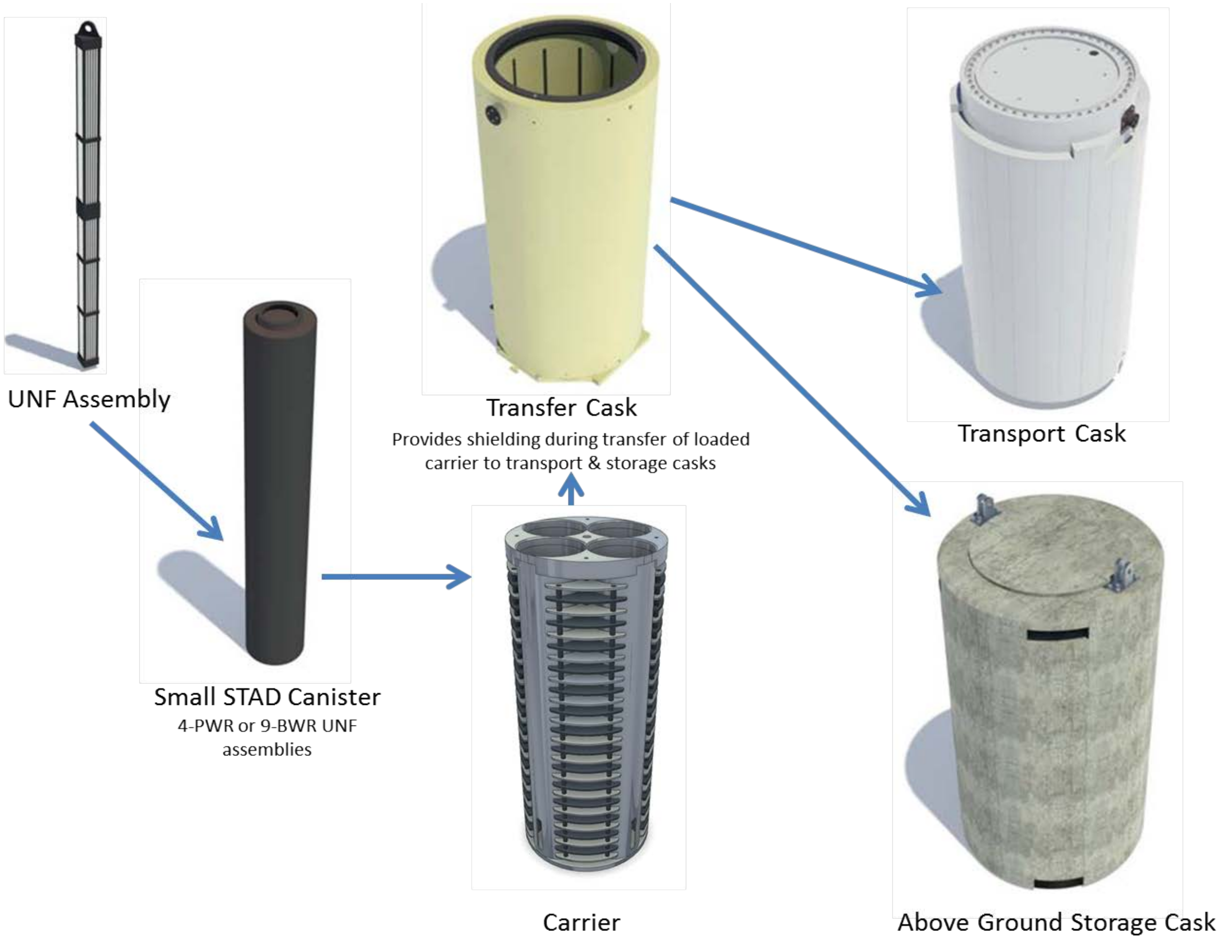


Figure 4: Overview of the Small STAD Canister System

Transfer cask equipment, similar to that used to load, process and transfer the high capacity DPC based systems currently used by the NPP utilities, would be used in the same way for the medium and large STADs. For the small STADs, a transfer cask would again be used, but in this case it would contain four STADs contained in the carrier. Because the carrier system allows 16 UNF assemblies to be handled at a time, even though the STADs each hold only four assemblies, this would mitigate some of the disadvantages of using small STADs instead of large DPCs.

The STAD canister carrier would provide operational alignment, multi-unit handling and shielding during fuel loading operations. The carrier is also a multipurpose frame which functions as a heat transfer device and structural component during storage and transportation. Because the carrier is open-sided it does not significantly impede heat transfer from the STADs and it also allows periodic inspection of the STADs by a remotely operated camera system when they are in dry storage, in the same way that single larger canisters in dry storage can be inspected.

The loading operations for small STADs using the carrier are shown in Figure 4. The carrier is filled with four empty small STAD canisters and is staged within the transfer cask, before placing the whole assembly into the pool. The 16 UNF assemblies are then placed into the four STAD canisters under water, the shield plugs put into place, the Transfer Cask and its contents withdrawn from the pool and the lid welding and closure operations previously described carried out in parallel for all four STAD canisters. The Transfer Cask contains, supports and shields the small STAD canisters and carrier during these operations, and during the subsequent transfer to either a transportation cask for immediate transfer off-site, or to a dry storage cask for on-site storage. Advice received during this study from welding specialists confirmed that, subject to the completion of a welding development program, it is considered feasible to weld the closures of 4 small STADs in parallel, if they are contained and supported in the carrier.

The system shown covers NPP sites with 125 ton crane capacities. NPP sites with 100 ton crane capacities would be accommodated by designing transfer casks with less shielding (if this can be shown to be acceptable), or by placing three (instead of four) STAD canisters in the transfer and storage casks, noting that loading three STAD canisters would require the use of a different carrier design, in order to avoid balance problems.

During this study an alternative to the small STAD carrier system was also assessed, this being the “STAD-in-Can” concept, in which four small STADs are enclosed in a closed sided can instead of an open sided carrier (Figure 6). However, it was found that this design impeded adequate heat transfer from the STADs, created difficulties with fully drying the inside of the can, impeded visual inspection of the STADs when in dry storage and imposed excess weight.

Figure 5: The Small STAD-in-Carrier System within a Transport Cask

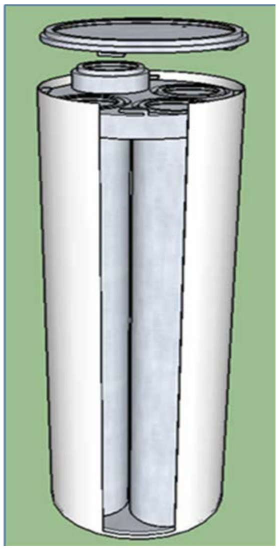


Figure 6: STAD-in-Can

The STAD-in-Can design is therefore not preferred over the STAD-in-Carrier design though, for completeness, it was included in the study of operational methods for filling canisters.

Design Analysis Work on the Generic Design for the Small STAD Canister

Structural, thermal, shielding and criticality analyses were carried out for the small STAD canister and small STAD carrier conceptual designs. Structurally the carrier design is essentially the blending of a typical dry cask storage design and the tube and disk fuel basket design. Instead of an array of fuel assemblies, there are four vertical sleeves, one for each of four small STADs, integrated into a single package. These four sleeves are bound together by upper and lower plates and supported radially by additional gusset type supports.

The results of the small STAD canister shell assembly and carrier structural analysis demonstrated that the small STAD canister shell assembly would satisfy the allowable stress design criteria for storage conditions.

The thermal analyses for small STAD transportation showed that the fuel cladding and STAD canister basket structures meet their respective temperature limits by wide margins, assuming a STAD canister heat generation level of 6 kW/STAD canister. This corresponds to heat generation levels of 1.5 kW per PWR assembly and 0.667 kW per BWR assembly, and an overall transportation cask heat generation level of 24 kW. The thermal analyses for STAD storage showed that acceptable fuel rod cladding and STAD canister fuel basket structure temperatures will occur for payloads of four PWR or BWR STAD canisters in a carrier within the storage cask, even with a STAD canister heat load up to 8 kW/STAD canister.

The shielding analyses for STAD canisters during storage showed that the peak dose rates on the cask side surface are between 80 and 90 mrem/hr, for PWR and BWR fuel, respectively. This is not significantly higher than that of other storage cask systems, given the bounding nature of the analyzed (62.5 GWd/MTU, 5 year cooled) assembly payload. The 25 mrem/year limit at the site boundary is the only 10 CFR Part 72 limit that applies for the storage cask. The maximum cask side surface dose rate necessary to meet this limit will be a function of the number of casks in the CISF, the CISF arrangement, the actual UNF payload loaded into the casks, and the distance to the site boundary. For transfer operations, the shielding analysis results show peak dose rates under 1.0 Rem/hr on the cask side surface under dry conditions, and dose rates under 100 mrem/hr on the cask side surface when the cask and STAD canister cavities are filled with water. The peak dose rates occur at the axial elevation of the peak burnup region of the fuel. These dose rates are acceptable and in line with industry experience.

For criticality control it is likely that moderator (water) exclusion would be employed as the primary means of control under the 10 CFR Part 71 hypothetical accident condition (HAC) for the transportation cask system. The double seal weld of the STAD canisters could be credited as the second barrier to water ingress (an approach for which there is precedent in cask system licensing). The transport cask containment boundary would be the first barrier to water ingress. However, analyses that model water ingress do have to be used to qualify the nominal “as loaded” configuration (containing intact fuel), per the requirements of 10 CFR Part 71.55(e). Criticality analyses that model water within the STAD interiors as well as between the STADs were therefore performed. The purpose of these analyses was to qualify the “as loaded” cask configuration, and provide backup (defense in depth) to moderator exclusion for the normal conditions of transport (NCT) and HAC configuration. The criticality analyses model the STAD canisters inside the transportation cask and, as the (outer) cask configuration does not significantly affect reactivity, and the transfer cask and transport cask materials are similar, the results of the criticality analyses are applicable for the transfer (loading) configuration as well.

For PWR UNF, three different configurations were modeled with water ingress, which reflect different licensing contingencies: (i) intact PWR assemblies, (ii) optimum pitch cladded PWR rod arrays and (iii) fully reconfigured (rubble) PWR fuel pellet array. For configurations (i) and (ii), it was concluded that the STAD canister could accommodate the entire U.S. spent PWR assembly inventory, without any need for payload reduction. For configuration (iii) it was found necessary to add borated stainless steel in certain places within the cask and carrier before a similar performance could be achieved under these extreme conditions.

For BWR UNF the same three configurations with water ingress were modeled. For configuration (i) the STAD canister in transport cask system could again accommodate the entire US BWR UNF inventory without the need for any payload reduction. For configuration (ii) payload reduction would be required for some UNF, though this could be partially mitigated by inclusion of borated stainless steel. For the extreme configuration (iii) it was found that the UNF that could be transported was limited to that with initial enrichments of 3.6% or less and that there were no plausible design changes that could mitigate this.

Certification and Fabricability Considerations for the Generic Design of the Small STAD Canisters

For certification and licensing of the STADs, issues covering aging management, the transport and storage of high burnup UNF, the use of both horizontal and vertical storage orientations, multiple STADs in a carrier, and the potential reliance on moderator exclusion were all studied. It was concluded that, although all these issues would be considered in detail by the NRC in response to a formal application, regulatory approval was likely for both the transport and storage Certificates of Compliance.

An evaluation of the ability to fabricate the small STAD canister system components was performed by team member Petersen Incorporated, who operate a state-of-the-art precision machining and fabrication facility, producing components for the nuclear industry as a core business to NQA-1 standards. This evaluation concluded that the components could be fabricated within current facilities and capabilities. They also have features that allow for uncomplicated manufacturing, which were arrived at following a “fabricability” review during a Team workshop, which resulted in some changes to the STAD canister fuel basket designs.

OPERATIONAL METHODS FOR FILLING STAD CANISTER SYSTEMS

Complementary to the generic design for a small STAD canister system, a study was performed to better understand, and to seek innovative solutions to, the operational impacts at the NPP sites of using small, medium and large STADs instead of the large DPCs currently being used. This work was intended to provide a better understanding of the tasks, durations, costs, equipment and human resources to move a specific number of UNF assemblies to dry storage over a fixed time into the three sizes of STAD, so this can be compared with that required when using large capacity DPCs. In this way the feasibility of the NPP utilities using STADs can be assessed with the goal of maximizing UNF management flexibility while minimizing utility impacts, potential re-packaging needs and overall system costs.

Constraints on, and Assumptions for, this Study

The Team's starting point for this study was to assume the three different capacity STADs: small (4PWR/9BWR), medium (12PWR/32BWR) and large (21PWR/44BWR) that had been identified by DOE for study, based on the results from the previous industry studies [4]. The medium and large STAD canister sizes were operationally assessed as single canisters, but the small STAD canister assessment used the generic design previously described in this paper, with the four-STAD-in-carrier system enabling 16 PWR or 36 BWR UNF assemblies to be handled at the same time. For all three STAD canister sizes the loading processes assumed several process improvements for internal drying and seal welding, while for the small STADs the loading processes also assumed that parallel seal welding and handling of four STADs at a time would be used.

In order to assess the performance of the loading processes developed for the three STAD sizes, nine representative NPP cases (four BWR and five PWR) were identified with varying refueling schedules (every 18 or every 24 months), numbers of reactors on site (1, 2 or 3), and including assumptions regarding the number of UNF assemblies to be moved from wet (pool) storage to dry storage every six years (Table I).

The Team also assumed that wet to dry loading operations could run up to 24 hours per day, seven days per week, and that a maximum of 12 continuous weeks would be available for a loading campaign, with a maximum frequency of one loading campaign per calendar year.

TABLE I: NPP Operational Cases Studied

Case	Reactor Type	Number of Reactors On Site	Operating Cycle Length (months)	Per Reactor Number of Assemblies to be loaded to Dry Storage every Six Years	Total Number of Assemblies to be Loaded to Dry Storage every Six Years
1	BWR	1	18	900	900
2	BWR	1	24	900	900
3	BWR	2	24	900	1800
4	BWR	3	24	900	2700
5	PWR	1	18	370	370
6	PWR	1	24	370	370
7	PWR	2	18	370	740
8	PWR	2	24	370	740
9	PWR	3	18	370	1110

The assessment started with determining the maximum number of assemblies that could be moved to dry storage in a 12-week window for each STAD canister size, beginning with currently understood dry storage operations (“Baseline”) and then applying the previously described process improvements (“Optimized”) to the various STAD canister configurations. It then progressed to determining the number of 12-week loading campaigns that would be required over a 6-year period for each of the nine plant cases. Finally, the team drew on its NPP operating experience and looked at the configurations of operating NPPs, in order to determine the practicality of performing the required number of loading campaigns.

Operational Approaches

For the medium and large STAD canisters, it was assumed that they would be loaded individually and would utilize a loading process that is similar to the process used by Zion*Solutions* (an Energy*Solutions* company) to load sixty-one 37-PWR DPCs in less than 52 weeks at the shutdown Zion Nuclear Power Plant, in Illinois. This process represents the current state-of-the-art for dry storage across the country and the size of the Zion loading campaign has provided valuable lessons learned, operating experience and operations data, which was fully utilized by the Team and is referred to as “baseline data”.

For the small STAD canisters, the Team knew that handling these individually would be a protracted process that would require improved loading practices and technological innovations to meet the throughput requirements. To streamline these processing operations, the STAD-in-carrier and STAD-in-Can systems previously described were therefore evaluated, which enable small STADs to be loaded, welded, dried and transferred in groups of four.

In conjunction with the loading processes, the Team also performed in-depth investigations of two major dry storage process technologies: welding/non-destructive examination (NDE) and canister drying, in order to identify improvements that would optimize canister drying and welding times. For welding improvements, according to a major welding vendor from whom we sought advice, welding four small STAD canisters, in parallel, using independent remote controlled welding machines is feasible, subject to the completion of a welding development program.

For drying time improvements the important parameters include:
- fuel basket design: self-draining can be enhanced and pooling and water retention minimized by careful design of the fuel basket,
- fuel assembly age and material condition: optimization of available residual heat by suitable selection of UNF with a range of cooling times, promotes water evaporation and hence minimizes water retention,
- neutron absorption material composition: utilization of non-porous metal matrix neutron absorbing material ensures that water is not absorbed and hence made difficult to remove.

Additionally, two other process technology improvements were assessed:
- the use of automated vacuum drying systems to replace existing manual methods was demonstrated to achieve reduced vacuum drying times and more consistent dryness conditions in each canister,
- the use of dual transfer casks was shown to enable one to be filled with UNF within the pool, while the other is being unloaded into a transport or storage cask at a separate cask transfer facility, typically located at or near the storage pad.

Parametric Studies

Time and motion studies (referred to as the “Parametric Studies”) were performed, via a three step process and utilizing (i) baseline Zion data, and, as discussed above, (ii) the welding process improvements, (iii) the improvements to canister drying processes, and (iv) the use of dual transfer casks.

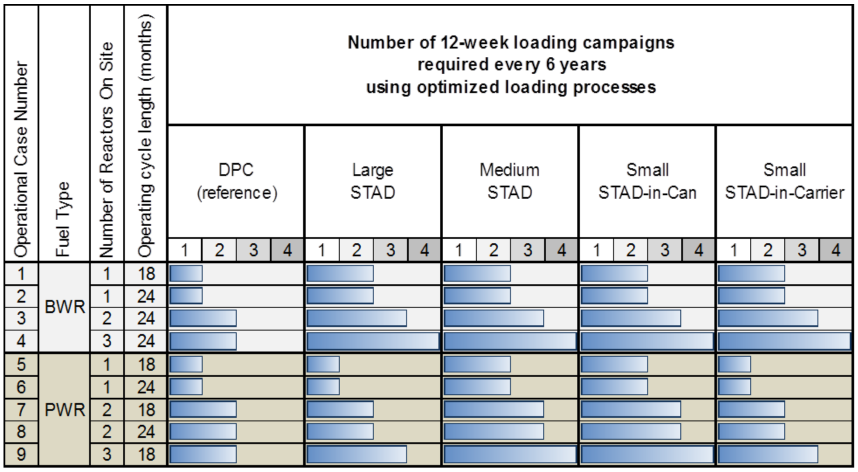
During Step 1 of the parametric studies, the maximum number of UNF assemblies and filled canisters that could be moved to dry storage in a 12-week window for each STAD canister variant was determined, beginning with currently understood dry storage operations (“Baseline”) and then applying process technology improvements (automated vacuum drying and parallel welding of the small STAD canisters) and dual transfer cask improvements (“Optimized”) to the various STAD configurations. During Step 2, it was determined whether each STAD variant could provide the throughput required for each of the nine plant cases studied and, if they could, the number of 12-week loading campaigns (assuming a maximum frequency one campaign per calendar year) that would be required over a 6-year period was identified. In determining the number of 12-week loading campaigns, a calculation was performed for each plant case and each STAD variant, to determine the “margin” between the plant throughput needs (i.e., the required quantities of fuel assemblies that need to be loaded to dry storage every 6 year period), and the peak STAD canister loading rate determined by the time and motion studies. This margin was in the form of a percentage and the criteria was to simply ensure that it was a positive value, rather than assigning an arbitrary cut-off value such as “greater than 10%”, or “greater than 5%”, etc. During Step 3, the margins were assessed between the required performance and the achievable performance and recommended loading frequencies identified for each of the nine plant cases.

For Step 1, the results are shown in Table II, noting that the “DPC (ref)” system refers to a DPC holding either 37 PWR or 87 BWR spent fuel assemblies. The purpose of showing this information is to provide a comparison between the performance of the STAD canister variants and DPCs at or close to the largest capacities being used in the industry today. As would be expected, all the STADs show a lower number of UNF assemblies being loaded in a 12 week campaign than can be achieved with the DPCs. The optimized processes improve the number of UNF assemblies that can be loaded into the STADS but this is still lower than for the DPCs. Looking at the number of DPCs or STADs that can be loaded in a 12 week campaign, this is comparable under baseline conditions, but the STADs loaded exceed the DPCs loaded when optimized processes are applied to the STADs.

TABLE II: Maximum Number of Assemblies and STAD Canister Variants per 12-Week Loading Campaign

System	Assemblies Per 12-Week Campaign				System	DPC, Large/Medium STAD, or Can/Carrier Per 12-Week Campaign			
	Baseline		Optimized			Baseline		Optimized	
	BWR	PWR	BWR	PWR		BWR	PWR	BWR	PWR
DPC (ref)	1131	555			DPC (ref)	13	15		
Large STAD	660	357	836	420	Large STAD	15	17	19	20
Medium STAD	608	252	768	300	Medium STAD	19	21	24	25
Small STAD-in-Can	468	224	756	352	Small STAD-in-Can	13	14	21	22
Small STAD-in-Carrier	504	240	864	400	Small STAD-in-Carrier	14	15	24	25

TABLE III: Number of 12-Week Loading Campaigns Required Every 6 years



Operational Case Number	Fuel Type	Number of Reactors On Site	Operating cycle length (months)	Number of 12-week loading campaigns required every 6 years using optimized loading processes				
				DPC (reference)	Large STAD	Medium STAD	Small STAD-in-Can	Small STAD-in-Carrier
				1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
1	BWR	1	18					
2		1	24					
3		2	24					
4		3	24					
5	PWR	1	18					
6		1	24					
7		2	18					
8		2	24					
9		3	18					

For Step 2, the numbers of 12-week loading campaigns required every 6 years are shown in Table III. This shows that, despite the lower number of UNF assemblies loadable into STADs in a given time, each of the eight STAD large, medium and small system variants (4 for PWR and 4 for BWR) evaluated has the potential to meet the throughput requirements for each of the nine plant cases investigated, assuming that dual transfer casks and the process technology improvements are used, i.e. the "Optimized" loading processes.

For Step 3, regarding the recommended loading frequencies, cases 4 and 9 in Table 3 have 4% and 9% margins, respectively, for some variants, and would be improved by moving to five or six 12-week loading campaigns every six years., which, as described in the following section, is considered to be feasible for the three-reactor sites represented in cases 4 and 9.

Optimized Loading Process and its Practicability at the NPP Sites

The Team drew on its NPP operating experience and looked at the configurations of operating sites with regards to the practicality of performing the frequencies of loading campaigns identified in Table III. The consensus for single unit PWR or BWR sites (Cases 1, 2, 5 and 6) is that the proposed loading frequencies could be accommodated, noting that 18 month operating cycles do lead to more refueling outages over time and thus less time to perform other large projects and often shorter windows to do so.

Dual unit BWR sites running on 24-month operating cycles (Case 3) require one refueling outage per year alternating between each of the units, and the ‘Refuel Floor Time’ available for spent fuel load-out is limited, so a large dry storage loading campaign every other year is desirable. This equates to three loading campaigns over a six year period and is consistent with what is shown in Table III.

For dual unit PWR sites running on 18 month operating cycles (Case 7), refueling outages alternate between the two units for two years and during the third year the site needs to implement an outage for both of the units. It is not desirable to perform a loading campaign during a year when both units will be executing a refueling outage. Thus, the ideal plan is to load fuel to dry storage for two consecutive years and then skip a year to enable the site to execute the outages for both units. This would equate to loading campaigns being performed during four of the six years and is consistent with what is shown in Table III.

For dual unit PWR sites running on 24 month refueling cycles (Case 8), an outage will be executed every year; alternating between the two units. There is no year where an outage is executed for both units. Thus, it is possible for these sites to perform three loading campaigns during each six year cycle. Table III shows that each of the STAD variants will be able to support this frequency.

For Cases 4 and 9, which are for 3 reactor sites and are reflective of the Browns Ferry and Palo Verde sites, respectively, loading operations currently take place annually and so would support the required number of loading campaigns in Table III. Both of these sites have unique configurations, i.e. at Palo Verde each reactor has its own pool and overhead crane, and at Browns Ferry, two of the reactors function as a dual-unit installation; with the other reactor functioning as a single-unit installation. These unique configurations emphasize the important part that consideration of the configuration of multi-unit reactor sites will ultimately play in determining whether loading campaigns utilizing smaller capacity (compared with DPCs) STAD canisters are able to support the required throughput rates.

CONCLUSIONS

- Whether large capacity DPCs may be able to be directly disposed in a repository is not known at this time, and will depend in part on future geologic disposal concepts and their capacity for heat removal.
- The use by the NPP utilities of smaller capacity STADs, in particular the 4PWR/9BWR size, could avoid a potential need to repackage fuel from DPCs before repository disposal, but this is dependent on developing ways to load such STADs at efficiencies approaching those of the DPCs.

- This paper has described a generic design concept for a small STAD canister system, which utilizes a first-of-kind carrier to allow four small STADs to be loaded, dried and handled in parallel from the pool through to storage and transportation.
- This design was shown to be potentially licensable, fabricable and its welded closure procedures shown to be practicable.
- A range of process technology improvements for the filling and internal drying of all three sizes of STAD were developed, together with a scheme for the use of dual transfer casks, to accelerate the loading, sealing and transfer of the STADs. With these process improvements in place, together with the use of the four STAD carrier system for the small STADs, our parametric study evaluation showed that, in theory, all three STAD canister sizes are capable of working at most, if not all, NPP sites evaluated, given a minimum loading campaign frequency of four every six years. This campaign frequency appears to be readily achievable.

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