# Dry Storage of Research Reactor Spent Nuclear Fuel - 13321

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## ABSTRACT

Spent fuel from domestic and foreign research reactors is received and stored at the Savannah River Site's L Area Material Storage (L Basin) Facility. This DOE-owned fuel consists primarily of highly enriched uranium in metal, oxide or silicide form with aluminum cladding. Upon receipt, the fuel is unloaded and transferred to basin storage awaiting final disposition. Disposition alternatives include processing via the site's H Canyon facility for uranium recovery, or packaging and shipment of the spent fuel to a waste repository. A program has been developed to provide a phased approach for dry storage of the L Basin fuel.

The initial phase of the dry storage program will demonstrate loading, drying, and storage of fuel in twelve instrumented canisters to assess fuel performance. After closure, the loaded canisters are transferred to pad-mounted concrete overpacks, similar to those used for dry storage of commercial fuel. Unlike commercial spent fuel, however, the DOE fuel has high enrichment, very low to high burnup, and low decay heat. The aluminum cladding presents unique challenges due to the presence of an oxide layer that forms on the cladding surface, and corrosion degradation resulting from prolonged wet storage. The removal of free and bound water is essential to the prevention of fuel corrosion and radiolytic generation of hydrogen. The demonstration will validate models predicting pressure, temperature, gas generation, and corrosion performance, provide an engineering scale demonstration of fuel handling, drying, leak testing, and canister backfill operations, and establish "road-ready" storage of fuel that is suitable for offsite repository shipment or retrievable for onsite processing. Implementation of the Phase I demonstration can be completed within three years. Phases II and III, leading to the deinventory of L Basin, would require an additional 750 canisters and 6-12 years to complete [1].

Transfer of the fuel from basin storage to dry storage requires integration with current facility operations, and selection of equipment that will allow safe operation within the constraints of existing facility conditions. Examples of such constraints that are evaluated and addressed by the dry storage program include limited basin depth, varying fuel lengths up to 4 m, (13 ft), fissile loading limits, canister closure design, post-load drying and closure of the canisters, instrument selection and installation, and movement of the canisters to storage casks. The initial pilot phase restricts the fuels to shorter length fuels that can be loaded to the canister directly underwater; subsequent phases will require use of a shielded transfer system. Removal of the canister from the basin, followed by drying, inerting, closure of the canister , and transfer of the canister to the storage cask are completed with remotely operated equipment and appropriate shielding to reduce personnel radiation exposure.

## INTRODUCTION

The scope of the demonstration is to provide a phased, optimized dry-storage approach for dealing with the Department of Energy (DOE) used nuclear fuel currently stored and anticipated to be received in L Area basin. The safe management and disposition of used nuclear fuel is an important responsibility of the DOE and has been impacted by the delays in locating, constructing, and licensing a repository site. Used fuel from government and research reactors is currently being received and stored at Savannah River Site (SRS) in the former L Reactor disassembly basin. Although there is a strong technical basis to support long-term pool storage, the ultimate disposition path will require removal of the fuel for transfer to a processing facility for uranium recovery, or to a repository site for disposal.

The fuel is in the form of aluminum-clad rods or plates containing uranium oxide, uranium silicide, and uranium-aluminum alloy, which are stored in aluminum (Al) bundles in underwater storage racks. Much of the fuel is highly enriched uranium, with relatively low burnup and decay heat. Based on the projected future receipts of DOE fuel, the existing basin will require modifications to increase the capacity for interim storage of these fuels. Although a small portion will require processing for stabilization, various options are under consideration for the disposition of the bulk of the fuel, including continuing wet storage, processing in the H Canyon separations facility for highly enriched uranium (HEU) blend-down, building a large Dry Storage Facility building, and shipment of non-Al clad fuel to Idaho National Laboratory (INL) in exchange for shipment of Al-clad fuel to SRS.

The program is based on the need to explore and define an optimal pathway for dry storage of the fuel pending ultimate emplacement in a repository. Although the L Basin does not pose the same risks as commercial fuel basins, the recent Blue Ribbon Commission Report (BRC) emphasized the national need for such dry storage approaches. It is anticipated that a cask and pad-based approach, modeled after that employed for commercial fuel, would provide a cost-effective alternative compared to other options.

The dry storage capability would be implemented in phases to provide safe and secure dry storage for the bulk of the DOE used nuclear fuel, as described below:

*Phase I:* This phase will demonstrate the capability to monitor the performance of used fuel (aluminum-clad and non-Al clad in current SRS inventory) under extended dry storage conditions. This effort would involve selection, packaging, drying, and storing of a diverse set of fuel types and forms using several casks, each containing several standard spent nuclear fuel (SNF) canisters, to demonstrate the technical and safeguards viability of dry storage. Twelve instrumented fuel canisters stored in three concrete casks will provide data to validate models predicting fuel performance and canister environment. An integral part of this mission will be the demonstration of the retrieval of the fuel from dry storage for transport to the H Canyon facility for processing.

*Phase II:* Dry storage will be expanded to accommodate future receipts of DOE-owned fuel from foreign and domestic research reactors starting in FY 2014. Loading of 110 fuel canisters in 22 storage casks will be provided. Dry storage of this fuel would eliminate the need for installation of additional fuel storage racks in the basin.

*Phase III*: This phase will provide “road-ready” dry storage for the remaining aluminum-clad and non-aluminum clad L-Basin fuels, including the damaged fuel in isolation containers. This will transition the fuel toward final disposition, and provide improved stability for damaged fuel currently stored in the basin.

The Phase III scope will provide approximately 570 loaded canisters in 115 storage casks as configured in Phase II, plus an additional 55 canisters approximately 4.3 m (14 ft) tall. The taller canisters are required to accommodate longer fuel elements, and will be stored in taller storage casks.

When final de-inventory is completed, the L Basin will remain in service to allow transfer of future receipts of foreign research reactor/domestic research reactor (FRR/DRR) fuel to dry storage, and unloading of stored canisters, if required, for repair or transfer of fuel to H-Area for processing.

Figure 1 provides a pictorial view of all phases of the dry storage program.

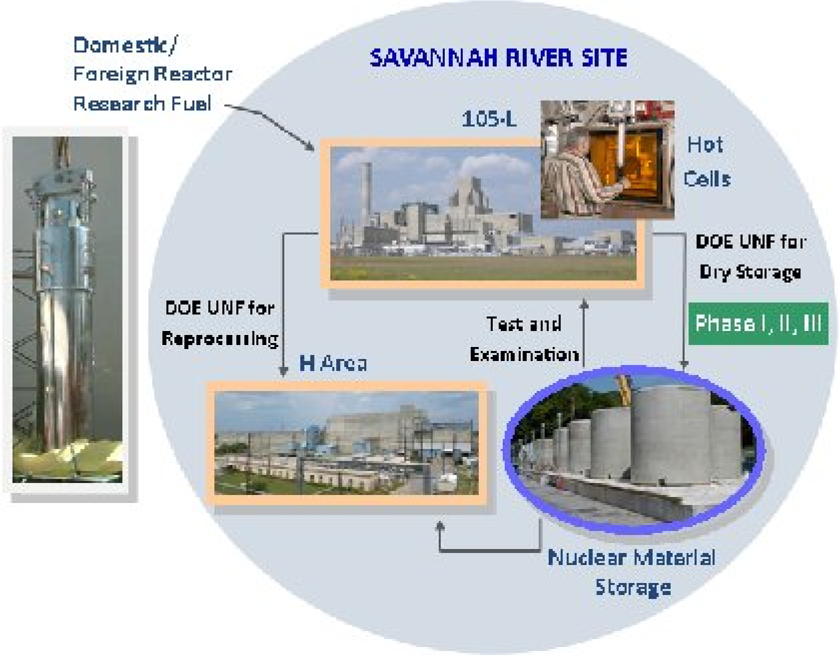

Figure 1: Dry Storage Mission Summary

The goals for the dry storage demonstration include:

- Demonstrate requisite technologies for dry storage of Al-based DOE used nuclear fuel (UNF)
- Provide technical basis data input for engineering design
- Provide field evaluated data for ES&H Analyses for dry storage
- Demonstrate of safeguards and security features
- Establish the envelope for safe dry storage of DOE owned UNF at SRS
- Initiate UNF dry storage capabilities at SRS

The critical technology elements that will be evaluated are:

- Drying technology and specifications
- Degraded fuel storage
- Demonstration of safe storage envelope for Al-fuel

## PERFORMANCE REQUIREMENTS

The primary requirement of the program is to provide “road-ready” dry storage of the fuel, where “road-ready” means that the fuel has been prepared and stored in a manner that does not require repackaging prior to offsite shipment. Dry storage demonstration of these fuels will replicate industry practices at commercial nuclear plants. Although the storage facility will not be NRC-licensed, it will comply with the requirements of 10CFR72, “Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High Level Radioactive Waste, and Reactor-Related Greater-Than-Class C Waste”. Data provided from storage of these materials will be used for comparison to both historical commercial experience and the performance of the Al-clad fuel in dry storage.

The storage of aluminum-clad fuel containing highly enriched uranium presents unique challenges to the performance of both the fuel and the canister. In addition, the configuration of the L Basin facility imposes constraints on the loading and preparation of the fuel to be stored. Finally, the requirement that the fuel be retrievable from storage for onsite processing has implications for canister design.

Because the fuel in inventory presents a wide range of fissile content, burnup, cooling time and other variables, a reference fuel assembly was developed for designing and evaluating a dry storage system. The bounding attributes [2] of this assembly are shown in Table I.

Requirements have been defined [3,4] to limit the degradation of the fuel materials placed into dry storage, which could compromise criticality safety, fuel integrity, retrievability of the fuel, or the disposition options.

Degradation of the fuel can be limited by controlling the environment within the canister. The system design must provide adequate cooling to limit deformation from cladding creep and diffusion of radionuclides through the cladding, or through pitting corrosion damage breaches in cladding at long-term storage conditions.

Fuel degradation can also result from corrosion of the fuel from reaction with water, present both as free water and chemically bound in cladding oxide film. In addition to corrosion, water reactions (both chemical and radiolytic) may produce gases that could result in container overpressurization, material embrittlement, or the production of flammable or pyrophoric compounds. The system design will provide for drying of the loaded canister, and backfilling with an inert gas (helium) to ensure the safety and integrity of the material in storage.

The performance of the fuel will be predicted by computational models based on physical and chemical phenomena of the fuel and its environment. Instrumentation will be required during the test phase (Phase I) to assess internal conditions and to validate these models. A series of sensors with a companion electronics package is required to collect, store, and transmit data from within the sealed canister. Sensors to be provided will allow measurement of temperature, dose rate, gas composition, and pressure.

Visual inspection via externally mounted camera will also be considered.

**Table I Reference Fuel Assembly for Dry Storage**

| Attribute | Application to SRS Dry Storage Demonstration Program | Metric |
|---|---|---|
| **Fuel Design** | **General fuel characteristics For basket design and canister loading** | **Material Test Reactor Equivalent – with 19 fuel plates** |
| | Dimensions | Bounded cropped: 65 cm L x 8.5 cm x 8.5 cm<br>Surface area: 1.746 $m^2$ |
| | Weight | Bounding: 10 kg |
| | Materials | Aluminum alloys for plate cladding and end plates. SS screws for plate assembly: Core materials: $UAL_x$, $U_3Si_2$, $U_3O_8$ in Al. |
| **Fuel Isotopic Content** | **Radioisotopes for: accident source term; shielding; heat load; NCS** | **Radioisotope content – dependent on application** |
| | Radiological hazard (source term) for accident analysis | Listed under L Basin Reference Fuel Assembly [5,6] |
| | Shielding hazard for handling and shielding design | HFBR fuel for gamma flux and spontaneous neutron flux |
| | Heat load for transportation, handling, and dry storage design | 25 watts, 3-year post-discharge of bounding fuel |
| | Nuclear criticality safety analysis | 410 grams U-235 per assembly with 93% enrichment |
| **Fuel Condition Post-Discharge and Storage** | **Describes spent fuel and challenges to interim dry storage in terms of confinement, retrievability, and other safety considerations of radiolytic gas generation from chemically-bound water** | **Degree of corrosion – in terms of metal consumption, including exposed fuel core (meat) material, and oxide corrosion product presence** |
| | Oxyhydroxide film - Boehmite | 50µm-thick adherent layer on all Al surface area. Total mass: 284 gm/assembly |
| | Oxyhydroxide Deposits – Gibbsite | Total mass: 5 gm/assembly |
| | Total Exposed Fuel Meat | 5% of total fuel meat |

## FACILITY DESCRIPTION

The L Area Material Storage Facility is a former nuclear reactor constructed in the early 1950s to produce materials for national defense and scientific research. In addition to the reactor vessel and support areas, the facility also contains a large water-filled basin that was used for disassembly and interim cooling of targets prior to rail shipment to separations facilities located in the site's F and H Areas. With the shutdown of the reactor and the end of its production mission, the disassembly basin has been converted for use as a storage facility for the onsite inventory of DOE fuels formerly stored at the Receiving Basin for Offsite Fuel (RBOF), and also for receipt and storage of DOE fuels to be returned from DRR and FRR facilities. In addition, the facility retains the capability to provide interarea shipment of spent fuel to H-Area for processing.

Key areas of the disassembly area that are important for the dry storage demonstration include:

- *Vertical Tube Storage (VTS) Basin*

  The VTS basin is 9 meters deep consisting of 24 lanes, each about 7.6 meters in length, equipped with a monorail system over each lane. Fuel assemblies are stored vertically in General Purpose (13 cm D x 4.3 m L) bundles or Expanded Basin Storage (13cm D x 3.7 m L) bundles equipped with a lid and handling bail.

- *Machine Basin*

  The Machine Basin has a depth ranging from 5.2 to 9.1 meters, and contains an underwater saw and tilt table. These components are used to perform mechanical operations on fuel, including bundle loading and unloading and cropping (aluminum end-plate removal) of fuel assemblies to improve loading efficiency and reduce the required storage space.

- *Transfer Area*

  The Transfer Area is used for the receipt, loading, and shipment of both onsite and offsite casks. The area includes a Transfer Bay for the receipt and staging of railcars or truck trailers carrying fuel casks, the Transfer Basin that provides for underwater loading and unloading of fuel, and the Shielded Transfer System (STS). The STS is configured to provide direct dry unloading of specific casks by providing a shielded transfer cask in lieu of water for personnel radiation exposure control. Cask movements are made using an overhead 77-MT crane with appropriate yokes and rigging to handle individual casks.

The facility is enclosed within a continuously patrolled security fence. The fuel in dry storage will be located on concrete pads within the fence to provide security for the HEU materials.

A plan arrangement of the L Basin storage area is shown in Figure 2.

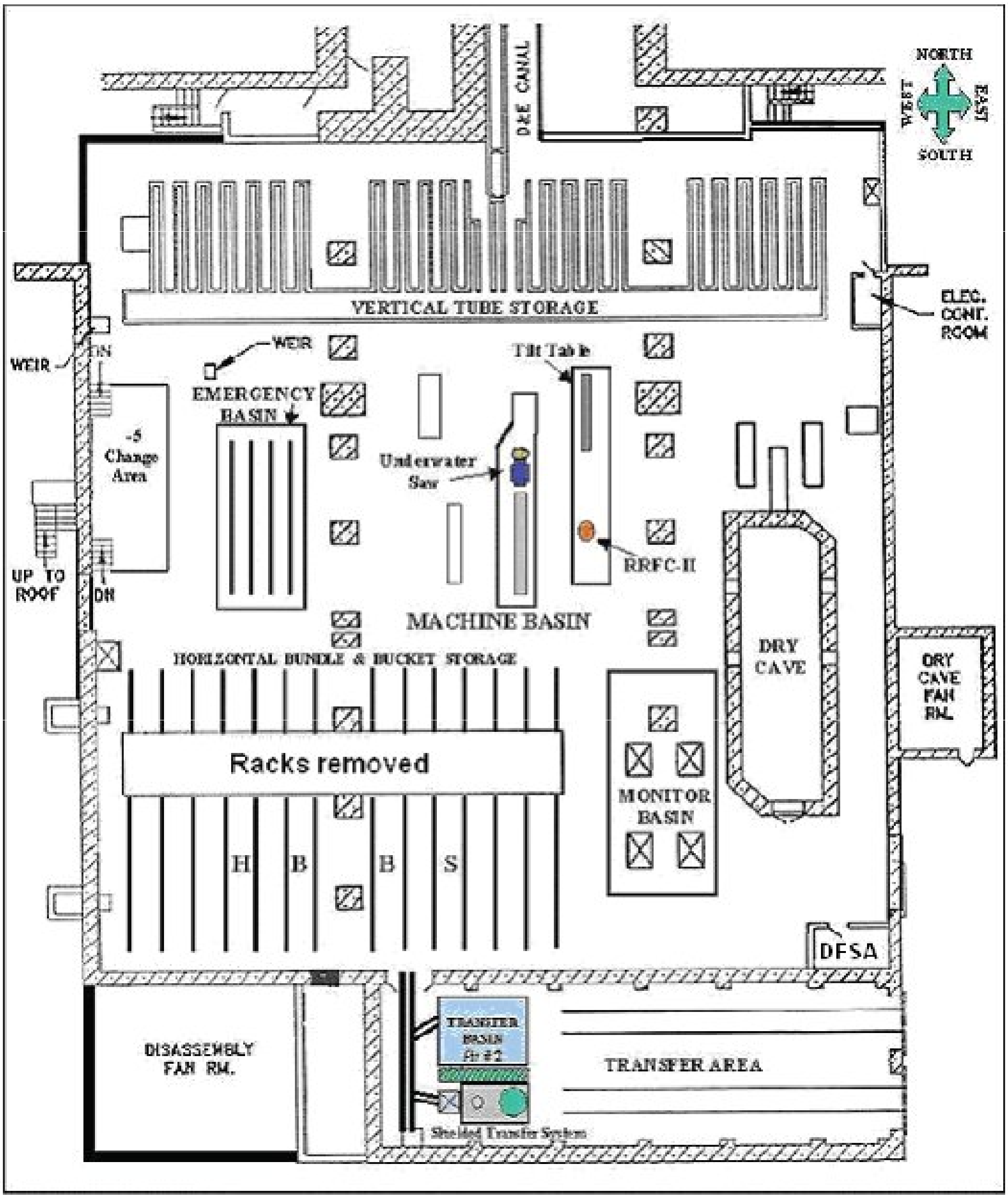

**Figure 2 L Basin Storage Area**

In addition to the disassembly basin area, the reactor building contains other large, open areas that are located within the heavily reinforced concrete structure. These areas will be used to complete the final drying, leak testing, backfilling, and closure of the canister after loading.

## CANISTER DESCRIPTION

The canister design is modeled after the 60 cm (24 in) diameter Multipurpose Canister Overpack (MCO) currently in use at Hanford for storage of N-Reactor fuel, but is shorter ( 3 m) for compatibility with the RH-72B shipping package and WIPP infrastructure. This canister design will handle 90% of the L Basin fuel inventory; taller canisters will be needed for the remaining 10%, for storage of longer fuel elements.

The Hanford MCO [7] is a cylindrical vessel 64 cm (25 in) in diameter and 4.2 m (13.6 ft) long, made of 1.3 cm (0.5 in) -thick 304L stainless steel with a bottom cap of 304L stainless steel 5.1 cm (2 in)-thick and a stainless steel shield plug, ~30 cm (12 in) thick, inserted at the top; the thickness of the plug will be evaluated and reduced based on the amount of radiation shielding required for L-Basin fuel. The original canister design included two filter elements to provide radionuclide confinement for degraded fuel. The total usable length of the cavity for the proposed canister with a 3 m outer height and a 25 cm shield plug is about 254 cm, with an inside diameter of about 58 cm. This usable length was achieved by eliminating the filter elements, which are not required due to the relatively good condition of the L Basin fuel. The MCO has a design pressure of 3.2 MPa (450 psig) and is built to Section III, Subsection NB, of the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code*. Each MCO receives an ASME "N" stamp. The design is deliberately robust to provide margin in its pressure handling capability.

As currently designed, the canister closure [8] is provided by a mechanical seal/locking ring combination. The closure system allows for drying, leak testing, and backfilling of the canister in preparation for storage. The mechanical seal will be relied on for confinement during the test phase (2-3 years) storage program; during this period, the instrumented canister will be routinely monitored and sampled. Following completion of the monitoring and sampling activities, the canister will be fitted with a cover cap to be welded over the mechanical closure to provide a redundant seal as required by 10CFR72. The mechanical seal provides rapid sealing of the canister for removal from the 105-L Transfer Area, and allows for resealing/reuse of the canister if the canister must be opened to retrieve fuel for processing. The mechanical seal will be adequate for the duration of the test, and the weld cap will be installed for long term storage to reduce monitoring and maintenance cost. A central suck-out line is used to remove water. Other vent and monitoring connections are provided with valves built into the shield plug and covered by removable cover plates.

The design approach of using the MCO-type canister as a basis for design evolved from requirements imposed for canister compatibility with systems for transportation and handing of remote-handled TRU packages at the Waste Isolation Pilot Plant, with limiting dimensions of 60 cm and three meters for diameter and height, respectively. Use of a shortened LWT-type canister with the existing STS limits the basket diameter to 33 cm and a total of only 3 baskets. This results in reduced fuel loading that will greatly increase the number of canisters required. This system will be used to handle the small quantity of longer, non-aluminum clad fuels in Phase III of the demonstration.

## FUEL LOADING

Fuel assemblies are stored in aluminum bundles for vertical storage in the L basin. For transfer to dry storage, bundles containing the selected fuel assemblies are transferred via monorail to the tilt table. Each bundle is opened, the fuel assemblies removed, and visual inspection is performed to record the “as stored” condition. The assemblies are loaded into buckets for underwater movement to the Transfer Bay, where the assemblies are transferred to fuel baskets.

### Baskets and Fuels

Typically the Al-clad fuels in L Basin are Material Test Reactor (MTR) type fuels (Figure 3) in the form of aluminum clad plates. They are normally box or round (tubular) in cross section, with a core of enriched uranium matrix in aluminum (U-Alx, $U_3O_8$-Al, or $U_3Si_2$-Al).

**Figure 3 Material Test Reactor Fuels**

The majority of fuel assemblies are less than 75 cm in height, allowing for a total of three baskets (with up to fourteen assemblies per basket, Figure 4) of fuel to be stacked in each canister. Assemblies with high U-235 loading may be restricted to as few as six compartments within each basket. A variety of fuels will be co-mingled to provide the greatest coverage of diverse forms, and provide efficient loading of the canister.

The proposed basket is modeled after the INL Type-1a basket [9] loaded in the DOE Standard SNF Canister. Although the INL basket contained a gadolinium (Gd) alloy, evaluation of a loaded canister determined that it was critically safe in storage and shipment without taking credit for presence of the Gd poison. The Gd was required by the repository design basis to ensure criticality safety after repository emplacement.

The taller canister (4.5m, 14.8 ft high) for longer fuel is based on the Nuclear Assurance Corporation (NAC) legal weight transport (LWT) cask design, with an ID of 35 cm (13.8 in). It allows up to 6 baskets with up to 7 MTR assemblies per basket. Longer fuels reduced the allowable number of baskets. For fuels with over 460 grams of U-235 per assembly, the loading was limited to four assemblies per basket, but with 7 assemblies allowed for fuels with less than 460 grams per assembly

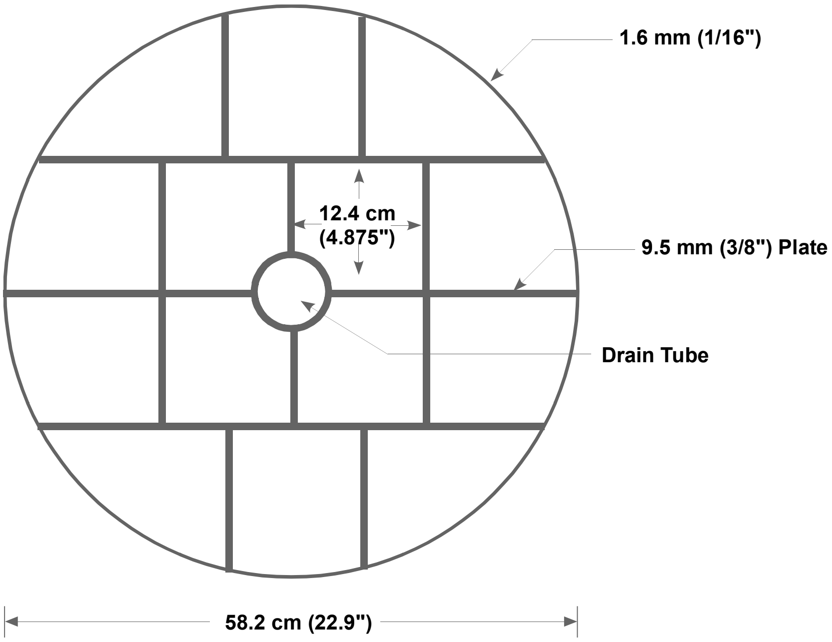

**Figure 4** Fourteen Compartment (Proposed) Fuel Basket

## Loading of Fuel

Fuel loaded in Phase I will be limited to a maximum of 75 cm (30 in) in length. Unlike commercial reactor facilities, the maximum depth of water in the L Basin Transfer Bay is 6.1 m (20 ft). Restriction of the fuel length to 75 cm allows direct transfer of loaded fuel baskets into the submerged canister with a minimum of 1.4 m (4.5 ft) water depth for radiation shielding. Loading of longer fuel will require the use of a Dry Transfer System (DTS) to provide radiation shielding when the fuel baskets are raised into the canister.

Basket loading operations for Phase I are shown in Figure 5. An empty canister is placed within a modified transfer cask and lowered into the Transfer Bay wet pit to the -6.1 m (-20 ft) floor for direct loading. The canister, as well as the annular space between the canister and transfer cask, are filled with demineralized water to minimize the potential for contamination of the canister. At the Transfer Bay, a fuel basket is positioned in the canister and secured with a support collar.

The buckets are raised, and the fuel assemblies are transferred individually from the bucket to the basket. When fuel transfers are complete, the loaded basket is lowered into the canister, and a new basket is positioned for loading. The process is repeated until the three baskets have been loaded into the canister.

When loading of the fuel assemblies is complete, the fuel-loading guide portion is removed (leaving the shield plug guide portion inserted), the shield plug is installed, and the shield plug guide is removed. The canister collar provides for a threaded shield plug locking ring that is inserted and rotated until securely in place. The locking ring closure tool has the capability for applying downward pressure on the shield plug and seal which compresses the seal and allows the set screws in the locking ring to be easily tightened. When the closure tool is removed, the set screws apply pressure to the shield plug seal thereby completing the leak tight closure system for transport to the Stack Area for drying. The shield plug is provided with a port and offset penetration (to minimize radiation streaming to the operators) which is used for vacuum drying the loaded fuel assemblies and for backfilling the canister with inert gas through a threaded port plug valve with metallic seal. A bolted port cover plate with gasket is provided to seal the port opening. In subsequent operations, the port cover plate and shield plug seal are leak tested. The final containment barrier for long-term storage is a cover cap that will be welded to the canister shell collar at the Stack Area.

The operations require a shielded transfer cask designed so that the canister top will be accessible for making connections and sealing, with adequate shielding on the top and sides. The shield plug in the canisters is an integral part of the overall shielding approach. The transfer cask will use a combination of steel, lead, and water shielding. The bottom of the transfer cask will use a scaled-down version of the standard commercial canister shutter door design. This will allow later transfer of the canister through the bottom shutter door into a storage overpack or shipping cask.

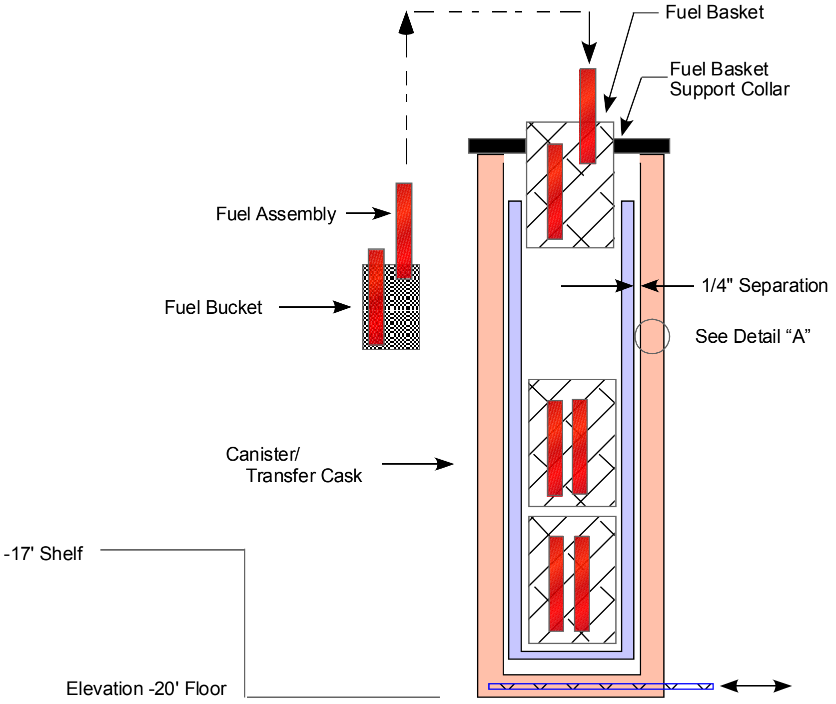

**Figure 5** **Phase I Canister Basket Fuel Loading**

The closure plug is sealed and the water drained from the canister before movement to the drying station. A cover plate is installed on the cask to prevent dropping the canister. The canister/transfer cask is lifted with the 77 MT (85 ton) crane onto a trailer transport to the drying station.

## Shielded Transfer Cask

The shielded transfer cask (STC) is used to provide shielding during loading, sealing, transport, and drying of the fuel canister, and to enable transfer of the canister into the concrete storage overpack. Two designs are discussed to bound the design of the canister for pre-conceptual design purposes. One approach would be to scale down the design of a commercial shielded transfer cask, and the other would be to modify the cask used by Hanford for the MCO. If selected, the commercial casks would have to be downsized to allow 6 mm (0.25 in) clearance on each side between the canister and inner cask surface, and to match height so that the canister shield plug would provide shielding, yet allow the top of the MCO to be accessible for making needed connections for drying, instrument hookup, and welding.

Pending a detailed analysis of the selected L-Basin fuels and the cask design, the shielding requirements of the cask are conceptually defined to be equivalent to those of the existing LWT cask, with variations as needed for the unique design features of the canister. The inner diameter of the STC is assumed to be 62 cm (24.5 in), allowing 6 mm (0.25 in) clearance on all sides of the canister. The inner cask wall is 19 mm (0.75 in) thick; between this inner cask wall and the 3 cm (1.2 in) thick outer shell, there is 14.5 cm (5.7 in) thick lead gamma shield. Neutron shielding is provided by a 13 cm (5.1 in) thick neutron shield tank with a 6 mm (0.25 in) thick outer wall, containing a water/ethylene glycol mixture. The neutron shield tank system includes an expansion tank to permit the expansion and contraction of the shield tank liquid without compromising the shielding or overstressing the shield tank structure. A maximum outer diameter of 127 cm (50 in) allows the flexibility of using the transfer cask in the dry pit with the STS, if desired. The transfer cask will be for on-site use only.

Another desirable feature of the STC will be the ability to fill and drain the annular cavity between the canister and the cask with demineralized water to protect against pool water contamination intrusion. Commercial casks typically have this capability now. In addition, were it proven necessary to circulate warm water in this annular space for fuel drying, the design would allow for circulation of up to 75 liters per minute of water. The cask design should be easily decontaminated and not present a contamination source from corrosion of components.

### Canister Closure

After fuel basket loading is complete, the canister is fitted with a closure plug to provide shielding during handling. The closure plug includes a mechanical seal that will provide confinement for the inert gas. The closure plug is equipped with penetrations for a vent, drain, thermowell, and relief valve connections. After the closure plug is secured, the transfer cask with the canister is removed from the wet pit, drained, and loaded onto a transport dolly in the Transfer Bay. A radiological survey is performed prior to removal of the transfer cask from the Transfer Bay.

The instrument package for each canister consists of instruments for pressure, temperature, relative humidity, hydrogen, oxygen, radiation monitors and a housing for calibration and transmitting signals. A simpler approach, using a magnetically coupled pressure indicator designed into the canister plug, combined with sampling of selected canisters every year to validate pressure and sample for gas buildup will be evaluated during the conceptual design phase.

### Drying

Drying of the fuel is required to prevent degradation of the fuel [10,11], resulting in canister pressurization and accumulation of hydrogen generated from the corrosion reactions and the radiolysis of water. Water may be present in any or all of three forms: free water in crevices or as a result of capillary action when removed from the basin, as chemically-bound water of hydration in the aluminum oxide surface coating, and absorbed as water in corrosion products.

Two approaches to drying have been identified and will be evaluated in the conceptual design phase. One approach would be the "cold (43°C) vacuum" drying approach demonstrated at Hanford on both zirconium and aluminum clad fuels. Subsequent monitoring validated the conservative models that had been developed for hydrogen and pressure generation. Another approach would employ the latest technology proven for use in drying commercial spent fuel. An example of this latter approach would be the Holtec "hot gas" drying system.

Fuel drying will be consistent with NRC-accepted methods described in NUREG-1536, *Standard Review Plan for Dry Cask Storage Systems.*

### Cold Vacuum Drying [12]

In this approach, vacuum drying requires the addition of heat to maintain the temperature at a nominal 43°C. This is accomplished by recirculating heated water at a flow rate of 60-75 liters of water per minute through the annular space between the canister and cask. The ability to seal the transfer cask shutter plate is required to maintain the water in the annular space. Additional heating could be provided if needed by recirculating the water in the transfer cask water jacket. In the Hanford application for SPR fuel, the maximum drying temperature is below 50 degrees C to avoid exceeding reactivity limits associated with uranium metal. However, only a small fraction of the SRS fuel would have this concern, so drying of this fuel could be addressed by the "hot gas" drying approach, but operated at a lower temperature with a longer cycle.

Residual water is removed from the canister using a vacuum pump (warm, inert gas may be introduced to the canister through the drain line to reduce the drying time, if required). The system is pulsed between hot helium backfill and full vacuum evacuation. After removing the free water vapor, the canister is evacuated, isolated, and confirmed to be free of water. A rate-of-rise check is patterned after a commercial practice in which the free water is removed at low pressure, and water removal is confirmed by reduction of pressure below the triple point. The drying system is provided with a demister and dual HEPA filter system to protect against inadvertent release of contamination. Water collected from the demister is periodically transferred back to basin.

When the rate-of-rise check confirms the canister is sufficiently dry, the canister is backfilled with helium. The canister is then transferred from the drying station in the Stack Area to the storage pad for insertion into the storage cask. The shield plugs and port seals are leak tested by installation of a hood over the top of the canister, and drawing a vacuum through a helium mass spectrometer leak detector.

### Forced Gas Dehydration [13]

An alternate drying approach that will be considered utilizes recirculated non-reactive gas to dehydrate the loaded canister. This technology is commercially available and approved by the NRC for drying spent fuel. Forced gas dehydration introduces a superheated non-reactive gas (e.g., nitrogen or helium) into the drained canister cavity, where it picks up moisture from the water remaining in the canister. The wet non-reactive gas is circulated through a condenser module to extract the majority of the water vapor from the gas, followed by a demoisturizer module in which the gas is cooled to a prescribed temperature ($T_c$), to freeze-dry the gas for removal of the remaining water to the specified limit. The dry gas leaving the demoisturizer is superheated ($T_h$) prior to recycle to the canister cavity. In this process, the introduction of the heated, non-reactive gas into the canister results in the absorption of water vapor within the canister by mixing with the water vapor already in the canister and evaporation of the liquid water within the cavity.

The temperature of -6°C corresponds to a water vapor pressure of 400 Pa (0.06 psi), which is consistent with the minimum vapor pressure requirement mandated by the NRC for dry storage packages prior to backfilling with inert gas. Therefore, a $T_C$ value of -6°C, set as the low temperature target for gas exiting the demoisturizer, would be expected to provide sufficient dryness of the non-reactive gas being circulated through the canister as to effect safe dry storage of spent nuclear fuel canisters, since the vapor pressure within the canister will tend toward the 400 Pa value as the system is utilized. The high temperature, $T_H$, could be set as high as several hundred degrees Fahrenheit. Higher values of $T_H$ result in increasing drying efficiency of the system and therefore decreasing drying times. It is anticipated that a temperature of 93°C would be adequate, and would avoid any safety issues associated with heating the fuel above the maximum allowed temperature. A detailed thermal analysis will be performed to optimize $T_H$, with consideration of maximum fuel temperature, canister pressure, and other potential limitations. A major benefit of the forced gas dehydration process is the elimination of system heating (other than gas superheating) to avoid water freezing during the drying process.

## Inerting

At the completion of drying, the canister will be backfilled with helium to a pressure determined by system models (up to 250 kPa (~36 psi), with a minimum helium purity of 99.9%. The canister inerting procedure is adapted from the Hanford MCO design basis, and is consistent the NRC-accepted method. The system allows re-evacuation and re-backfilling with helium and is designed to allow sampling before final closure, if required. Upon completion of canister loading, drying, and inerting, the system is capable of verifying that the gas fill of the canister interior is at a pressure level that is expected to maintain a non-reactive environment for a minimum of 40 years. The NRC has previously accepted specifications that incorporate an overpressure of approximately 14 kPa (~2 psi) and container leak testing as conditions of use for satisfying this requirement.

## Transfer to Storage Cask

The storage casks (Figure 6) are nominally 3.3 m (10.8 ft) diameter steel and cylindrical concrete vessels that provide for vertical storage for fuel canisters. A total of 150 casks will be required for the complete deinventory of L Basin. More than 90% will contain the shorter 3 meter tall canisters, which can be placed in shorter (4.3 m tall) casks.

The casks contain air inlets and outlets at the bottom and top, respectively, to provide natural convection for canister cooling. Under the steel and concrete lid, up to five canisters are arranged in a polar array, positioned using a spacer grid. The spacer assures that there is at least a 5 cm separation between canisters for criticality isolation; this would provide a 20 cm (7.9 in) center to center separation between adjacent elements.

The storage casks are designed to withstand all applicable natural phenomena hazard events, including non-mechanistic tip over, tornado wind and missiles, flood, earthquake, explosion, and overpressurization, to ensure material confinement and criticality safety of the stored fuel.

**Figure 6** **Storage Casks**

For loading each canister, the concrete lid is removed from the storage cask. The adapter collar is positioned on the metal shield plate over the designated loading position. The canister/transfer cask is positioned above the collar, and lowered into position (Figure 7), The canister cask is grappled and slightly raised to take the load off the shutter door, the shutter door at the bottom of the transfer cask is opened, and the canister is lowered into the storage cask (Figure 8) using a grapple. When the canister is in place, the grapple is raised, and the transfer cask is removed. After placement of the canister within the storage cask, the adapter collar is removed, and instrument connections are made to the canister. When complete, the instrument tube bundle is routed through the air outlet to a manifold for connection to a data acquisition system. Following instrument connections, the storage cask lid is placed in the storage cask.

Following completion of test program, the twelve instrumented canisters will be fitted with a welded cover cap to provide a redundant seal for long-term storage of the fuel.

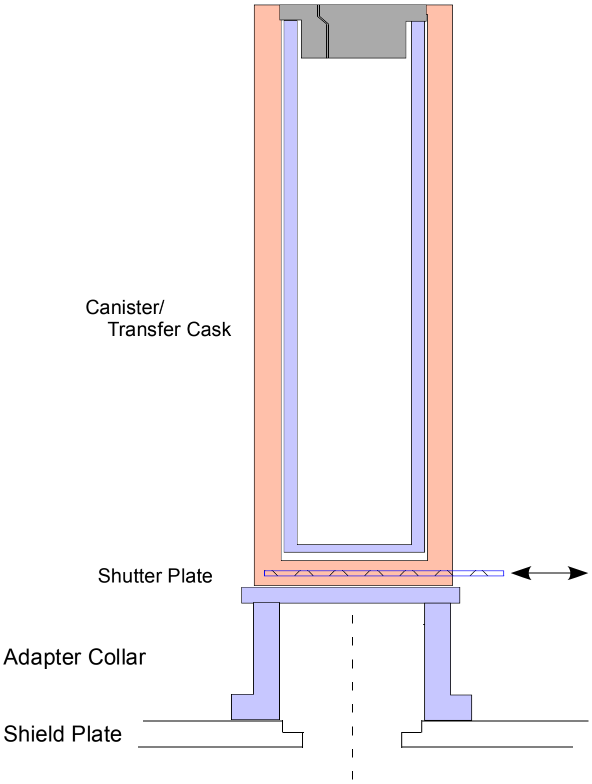

**Figure 7** **Canister in Loading Position**

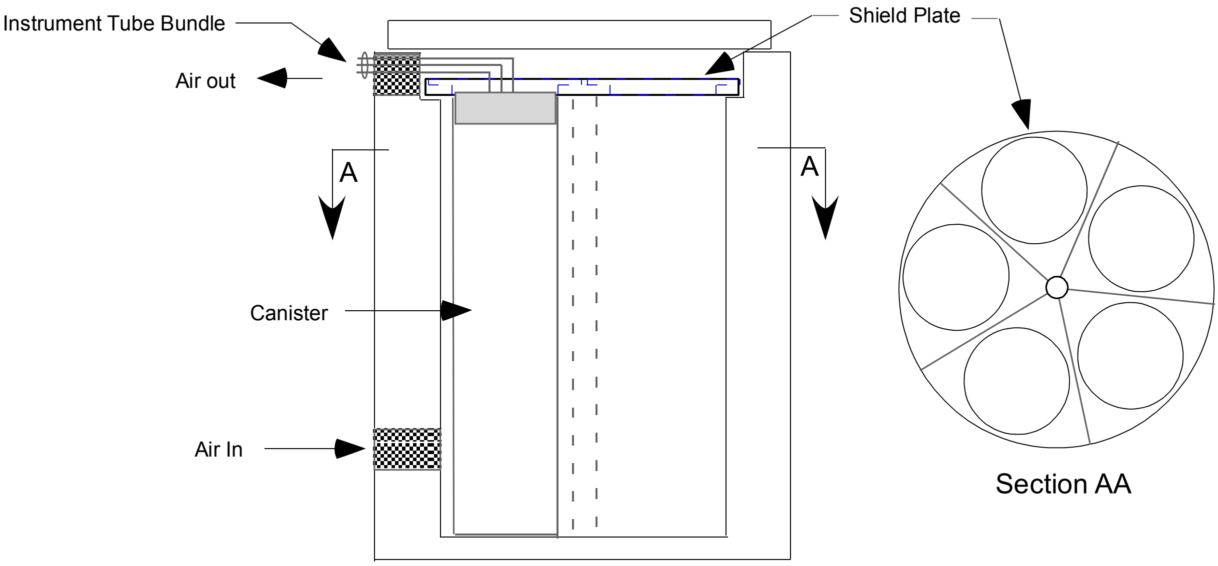

**Figure 8** **Storage Cask Canister Configuration**

## R & D TO SUPPORT DRY STORAGE

In preparation for dry storage of the aluminum-clad HEU fuel, critical technology must be developed and demonstrated. Evaluation of the critical technology elements ensures that all key issues are addressed and that practical, efficient, and economical solutions to these challenges result. Additionally, evaluation of these technology elements will be required prior to implementation of the subsequent program phases. An overview of the individual needs and a brief statement of the issues and intended approach are provided below.

### Drying approach and protocol for free water removal

Experimental testing will be performed on surrogate fuel assemblies to determine the effectiveness of both Cold Vacuum Drying and Forced Gas Dehydration methods of water removal from simulated corrosion-damaged fuel. As discussed above, canister drying is a critical step to providing safe, retrievable long-term storage for aluminum-clad fuel. System performance will be evaluated with respect to mathematical models to select the best system and optimize process parameters.

### Evaluation of radiolytic gas generation (“G-values”) [14]

SRS fuel has been observed to have boehmite ($Al_2O_3{\cdot}H_2O$) as the predominant oxide for fuels that were oxidized at temperatures above 80°C and to have gibbsite ($Al_2O_3{\cdot}3H_2O$) at oxidation temperature below that temperature. The bound water content of the mono-hydrated aluminum oxide, boehmite, contains only 33% of the bound water content in tri-hydrated aluminum oxides, including gibbsite, on the basis of moles of water per mole of aluminum. This water content would be considered in both thermal decomposition reactions to yield water, and in radiolysis reactions that could evolve gaseous hydrogen and oxygen. Therefore, an effort will be required to verify that the information for the assumed five grams of gibbsite limit per assembly as listed in Table 1 is valid. Gibbsite is typically not well adhered and any excessive amount can be readily scraped off the fuel prior to loading.

The basis for identifying a bounding condition for G-values is not present in the available literature. Recommended bounding G-values for the generation of molecular hydrogen and oxygen due to incident gamma radiation for a number of materials are based on empirical relationships to literature data review. However, review of literature data reveal that the recommended bounding relationships were developed without consideration of the hydrated aluminum-oxide. The majority of the very limited number of the data points for hydrated aluminum-oxide included in the plots that were generated appear to greatly exceed the values estimated by the recommended bounding relationships. Further, the test results indicate that only a small range of very low values of weight percent water in the solid oxide matrix (< 4.6 wt%) were included in the tests. The highest reported G-value for molecular hydrogen production due to gamma radiolysis in alumina ($Al_2O_3$) is 1.4 mole hydrogen per 100 eV absorbed by the matrix. Sub-stoichiometric oxygen production was observed in the same tests, indicating a trapping of some of the evolved oxygen in the oxide structure. Test data were not available to quantify the sub-stoichiometric oxygen production. Based on these observations, a maximum G-value for oxygen production due to gamma radiolysis 0.7 mole oxygen per 100 eV absorbed by the alumina matrix is inferred. As mentioned, the data reported in the literature cover only a small finite range of possibilities with respect to water content, and data for alumina is only available for gamma radiolysis.

To date, there is insufficient data in the literature, and no firm basis, to identify bounding molecular production rates for oxygen and hydrogen due to radiolysis in aluminum hydrated oxides. Therefore, laboratory testing will be conducted to establish applicable G-values for oxygen and hydrogen production for the range of conditions expected in the dry storage canisters at SRS. Further, this laboratory testing will establish the bases for the identification of bounding radiolysis induced oxygen and hydrogen production rates due to the mixed radiation environment expected during dry storage.

### Evaluation of sensors for on-line verification of fuel and canister performance and verification of safe storage [15]

To ensure the safety and security of spent nuclear fuel during long term storage, it is essential to understand the degradation mechanisms of materials involved, and to be able to monitor the relevant environmental, fuel bundle, and container conditions. Prognostic health monitoring is a critical research need regarding infrastructure degradation and will aid risk management decisions regarding the need to access, retrieve or move stored spent nuclear fuel in the future.

An in-situ monitoring system would allow for the condition of the fuel and environment in their inner cask to be verified in real time, without having to break the seal on the inner cask. An effective monitoring system must be able to drive sensors, collect data from sensors, and transmit data to a remote data logging system. Effective monitoring will be needed to not only assess internal conditions but also to verify and validate models of the radiolytic g-values developed under the SRNL test program. These monitoring needs will be addressed by constructing a test manifold in SRNL comprised of sensors to monitor relevant conditions and develop the electronics package for collection, storage, and transmission of data from within the sealed cask, with the focal point of the testing being the evaluation of long-term performance as a result of radiation exposure of the sensors.

Temperature information relates to physical changes in cladding material (especially zircalloy) and adherent corrosion products (hydrated gibbsite releases water molecules at 60ºC, hydrated boehmite at 400ºC). Temperature also affects gas pressure in the vessel.

Radioactive dose rate information provides the basis for determining cumulative dose rates over the duration of exposure.

Gas composition information indicates whether the cask seal integrity has been compromised, whether hydrogen is being generated, and whether moisture is present in the vessel and what quantities are attendant with each. The issue of hydrogen gas may only be related to corroded aluminum clad fuel.

Pressure information can be correlated to temperature and gas analysis enabling determination of the cause of pressure changes; for instance: decay heat, diurnal heating/cooling, or other external heating or cooling.

Visual information gathered with a camera from the inside of the vessel (fiber optic lens to external camera) supplements the information gathered by other instruments, primarily as it relates to cladding condition and corrosion products.

Seismic sensors (accelerometers) on the canister and on the cask would provide supplemental information if another seismic shock occurred in the area (as the recent 5.9 earthquake in Virginia was felt at SRS). Although these events can’t be predicted with much accuracy, having this very inexpensive instrumentation on the test vessels could provide rare and valuable information related to pad storage and canister and cask design.

## CONCLUSION

A pilot program providing dry storage of aluminum clad used nuclear fuel in instrumented canisters will provide technical data that will support safe, long-term dry storage of similar fuels. The results of the pilot program will allow for de-inventory of all fuel currently in pool storage in the L Basin, and result in approximately 750 canisters stored in 150 concrete casks. Transfer of the fuel to dry storage is an interim step in disposition of the fuel that will eliminate the need for installation of additional storage racks in the basin, and allow more time for a programmatic decision to process or dispose of the material.

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