Technical Issues Affecting the Transport of Dual Purpose Casks*

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INTRODUCTION

Spent fuel storage pools at many nuclear reactors in the United States have already or will soon be filled to maximum capacity. Approximately 50,000 metric tons of uranium (MTU) spent fuel will be discharged by the projected 2003 start-up date of a federal disposal system. Of this, approximately 6,000 MTU will require storage outside existing or projected pool storage capabilities (DOE, 1988). At-reactor dry storage of spent fuel, including vault, caisson, and cask systems, is being considered as an alternative to accommodate this excess fuel.

Two dry storage cask concepts are among those under consideration. One involves placing spent fuel in storage-only casks (SOC) until a monitored retrievable storage (MRS) facility or repository is open when the spent fuel would be transferred to a transport-only cask (TOC) for shipment. The second option, the dual purpose or transportable storage cask (TSC), is a system that would serve for both storage and later transport without requiring the spent fuel to be unloaded.

To carry out its purpose, a TSC must be shipped directly from a storage facility to a disposal facility without first being opened to evaluate the cask or the fuel. To assure that both the fuel and the cask are in a transportable condition after 20 to 40 years of storage requires: (1) a definition of expected storage conditions; (2) an assessment of the impact of expected storage conditions on the reliability of the components and functions of the TSC during transport; and (3) the development of an overall TSC system design and operational strategy which ensures that TSC transport reliability meets or exceeds that of a transport-only cask. The later requirement is related to defining what appropriate design features, pre-shipment inspections, and/or alternative fuel and cask monitoring requirements are necessary during long-term storage to ensure the cask will meet transport performance requirements during later transport.

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* This work performed at Sandia National Laboratories, Albuquerque, New Mexico, supported by the United States Department of Energy under Contract DE-AC04-76DP00789.

** A United States Department of Energy Facility

EXPECTED FEATURES OF A TSC SYSTEM

Some distinctive design, development, and operational features of a hypothetical TSC system are illustrated in Figure 1. This system is comparable to that used for a TOC and is designed to ensure that a TSC: (1) initially meets regulatory design requirements and thus is capable of providing adequate safety during both normal and accident conditions of transport; (2) maintains that capability throughout the service life of the cask; and (3) enters transport in an as-intended condition, i.e., the cask components and fuel contents are correctly assembled into a transport cask. This system can be partitioned into a number of discrete activities. The first feature or activity within the system involves defining appropriate technical safety limits for the functions of the system. Most, if not all, technical safety limits are already prescribed by storage and transport regulations. Environmental conditions must be defined so that performance requirements can be derived which together with technical limits result in an adequate design basis for the cask (U.S. Code of Federal Regulations, Title 10, Parts 71 and 72). The normal and accident conditions of transport provide most environmental conditions for transport. Consideration of site-specific storage conditions such as seismic provisions are required by 10CFR72. For some cask functions, such as criticality, the commonly imposed environmental conditions (maximum reflection and moderation) assume multiple failures of cask safety features and operations have occurred. For others such as containment, the system is assumed to be correctly assembled prior to applying the regulatory accident environment conditions. There are no analogous "normal conditions of storage" for transport evaluations.

The pre-use acceptance evaluation of the functional capability of a TSC should not differ from that of a TOC. Fuel acceptance is included in Figure 1 as an operational requirement because the design basis' fuel characteristics are not likely to correspond to worst-case characteristics in the fuel inventory. This operational step should not be different from similar requirements for a TOC.

The next activity in Figure 1 involves post-loading inspection and the initialization of storage-cycle data. This step is essential to base-line initial TSC system conditions so that trends may be followed during future performance assessments. The type of data needed depends on an as-yet-undefined design basis.

The loaded TSC will then be monitored in some fashion during the storage period. The objectives of validation monitoring are: (1) to ensure that the design basis environmental conditions are not exceeded; and (2) to validate design assumptions regarding the post-storage characteristics of component materials. To meet the first objective, environmental monitoring would likely be required for all casks. The second objective could be met by periodic evaluations of storage environment effects on components and fuel in a sample of "control" casks. This approach is identical to current test practices for consumable components of TOCs. For the approach to be successful, the monitored test specimens and the imposed environment must represent all potentially affected components and cavity environments.

The pre-shipment functional or performance assessments illustrated in Figure 1 are analogous to the periodic maintenance requirements for TOCs. Assessments of fuel condition and certain other parameters will involve integration of

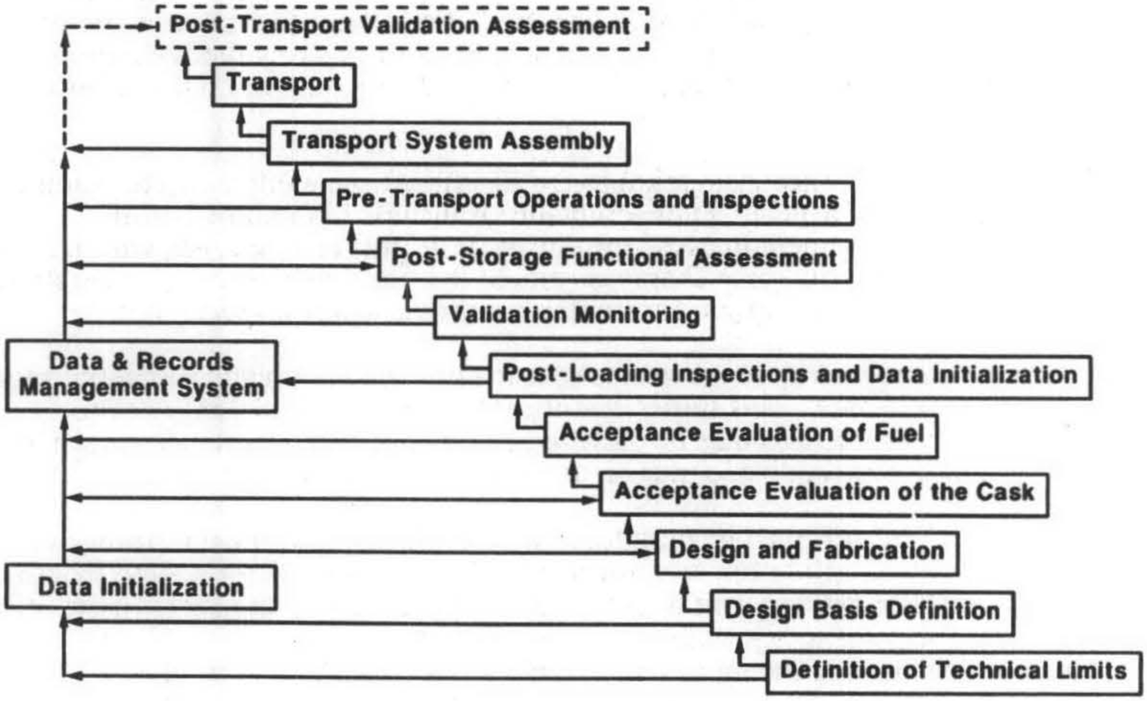

Figure 1. Expected Features of a TSC System

environmental data, whereas assessments of shielding and seal integrity, for example, may involve specific measurements. Many of the pre-shipment tests specified by transport regulations such as exterior dose rate measurements would be superseded by these detailed functional assessments. Those that remain, such as a contamination survey, are straightforward and should not require any special consideration for the TSC concept. The assembly of the transport system involves the installation of safety components, such as impact limiters, and the placement of the TSC on a transporter. From a fit-for-transport perspective, these operations are no different than for a TOC.

The final system operation depicted in Figure 1 is a post-transport validation assessment. After unloading at a receiving facility, some incoming TSCs could be subjected to maintenance inspections and again placed in service for transport or other use, or be subjected to destructive evaluations.

In summary, a concept for the design and operation of a TSC system can be developed. The transport reliability of a TSC may be comparable to or possibly exceed that of a TOC. Many accepted dry storage and TOC practices that ensure the reliability of design, fabrication, and operational steps already exist that are directly applicable to the TSC concept.

EXPECTED STORAGE ENVIRONMENT EFFECTS ON SPENT FUEL AND CASK MATERIALS

Important technical issues that arise because of uncertainties related to the storage environment are summarized in Table 1. Potential storage effects on the failure modes listed in the table are sufficiently different for a TSC concept in comparison to a TOC concept that extra consideration must be given toward limiting their potential for causing failure. Other failure modes are equally important to both the TOC and TSC concepts but are not distinctly different, and an acceptable approach exists that has been demonstrated by previous TOC or reactor operations. To meet regulatory requirements, two technical issues must be addressed: (1) definition of a normal condition of storage environment, and (2) identification of the effects of that environment on the integrity of the spent fuel and the reliability of the criticality control, shielding, containment, and heat transfer capabilities of the cask. An important consideration for TSC transport, then, is the expected condition of the fuel and cask materials after storage. While the materials may not have failed, the materials' properties may have changed (e.g., become embrittled), so that subsequent transportation could lead to either fuel cladding or cask failure.

Expected Condition of Spent Fuel Following Long-Term Dry Storage

Pertinent spent fuel data were evaluated to determine the potential for significant cladding degradation or failure during storage. Comprehensive assessments of degradation phenomena have identified creep rupture, stress-corrosion cracking, cracking associated with hydride formation, and oxidation as the only viable degradation mechanisms for spent fuel cladding (Cunningham et al, 1987; Johnson and Gilbert 1983). Fuel oxidation becomes an important cladding degradation mechanism for breached fuel rods only if air or water is introduced into the storage atmosphere.

TABLE 1

TSC TECHNICAL AREAS WITH DATA OR EFFECTS UNCERTAINTIES

CASK FUNCTIONAL CATEGORY	TECHNICAL ISSUE
Containment	Spent Fuel Integrity after Storage Seal Reliability after Storage Corrosion of Welds during Storage Changes in Structural Properties of Containment Materials during Storage
Criticality Control	Corrosion of Welds during Storage Changes in Structural Properties of Basket Materials during Storage
Heat Transfer	In-Service Deterioration of Heat Transfer Paths
Shielding	Environmental Degradation of Neutron Shield
All	Design Basis Internal Environment Definition Standardization of Procedures for Record-Keeping and Data Processing

Based on the experience available, an estimate can be made of the expected condition of spent fuel after long-term dry storage in certain environmental conditions. The degradation mechanisms, except for cladding oxidation, all produce failure by a slow crack-growth mechanism. Any resultant defects, e.g., from stress corrosion cracking (SCC) or creep rupture, are in the form of pinholes or small cracks varying in size from 1 to 30 μm (Tassoji et al, 1985). Such cracks will release fission gas and can provide a path for subsequent oxidation of fuel if air is present. However, the overall integrity of the fuel element is maintained. After the cladding has breached and gas is released, the internal pressure drops; hence, the stress in the cladding decreases. Gross ruptures or breaches beyond the size of a pinhole are not predicted and have not been observed in any tests or demonstrations to date.

Transportation regulatory guidelines indicate that defects larger than pinholes or hairline cracks in the fuel cladding are not allowed (MacDonald 1984). The condition of spent fuel should therefore still be within a transportable condition after a long-term dry storage period. The response of the spent fuel cladding to dynamic loading encountered in handling and transportation has been assessed (Bosi 1981). Results of this analysis indicate that spent fuel cladding, even with large assumed flaws, has fatigue-fracture integrity well in excess of that needed to survive cyclic transport loads.

Expected Degradation of Cask Materials and Components During Dry Storage

Available data were evaluated and some complimentary analyses were performed to evaluate the potential for significant degradation of cask components and materials during dry storage. Many cask materials are affected by gamma and neutron radiation, temperature, and other environmental factors during dry storage. The results of scoping calculations indicate the expected radiation damage in metallic cask materials produced by gammas and neutrons during a storage cycle is 1 to 2 orders of magnitude less than that required to produce observable degradation in the mechanical properties of iron-based alloys, copper, or aluminum. Also, poison burnout and helium generation in a borated basket material from neutron absorption is insignificant.

Maximum dry storage temperatures in the range of 300-400°C, depending on internal fuel rod pressures and cooling times, are currently recommended for inert and nitrogen gas cavity environments (Cunningham et al., 1987). This is too low to result in bulk diffusion behavior in iron and copper alloys. Significant microstructural or property changes in iron or copper alloys also are not produced. This lack of significant effects from long-term, low temperature aging is based on the premise that these cask materials are in a relatively stable metallurgical condition. If a material is thermodynamically unstable, the driving forces would be very high and the diffusion distances short. In these cases, even the low temperatures of the casks environment can produce significant property changes. Data are too sparse in some areas such as aging of gamma shielding materials, to make a valid judgment at this time. Additional data is also needed on the aging of neutron shielding materials. Samples of these materials could be evaluated prior to shipment.

It is highly unlikely that any elastomeric seal material subjected to the temperatures and radiation of the storage environment would retain sufficient resilience to maintain seal during a later dynamic transport environment. Metallic seals may also be subject to long term creep and stress relaxation. Thus a separate closure installed prior to transport that seals the storage closure and all other penetrations may be the only alternative to closure removal and seal replacement prior to TSC transport.

Long-term dry storage of spent fuel in casks should not have any detrimental effects on the heat transfer characteristics of those casks. With decreases in the decay heat generation rate of the spent fuel, fuel and cask temperatures should always decrease with time under normal operating conditions.

Most metal alloys will undergo some property changes when heated at an elevated temperature for a sufficiently long time. Metallurgical changes could occur in the cask materials after aging 40 years in the moderate-to-low-temperature storage environment. Aging processes such as precipitate coarsening, segregation, or grain growth that could alter properties are diffusion-controlled and should be relatively slow at the relatively low storage temperature. This can be verified by control cask monitoring.

Some changes such as crystallographic transformation can be very rapid once the critical temperature is reached, however. Any process that requires atom transport within the grain volume will be controlled by bulk diffusion. It is feasible, however, that there could be some coarsening of grain boundary precipitates as a result of diffusion along the boundary. The effects should be slight in iron and copper alloys but are difficult to quantify because of insufficient data.

Currently, licensing requirements for dry storage applications in the U.S. require maintaining an inert or nitrogen cavity gas atmosphere for the duration of the storage period. Degradation processes of cask internals from corrosion in a dry, moisture free, inert or nitrogen atmosphere should be severely limited and were not considered in this analysis. Because activities are underway to license dry storage in air, the use of air as a storage gas may need to be re-evaluated at a later date.

Most available data on spent fuel and cask materials suggest that currently recommended temperature limits in an inert or nitrogen gas cavity atmosphere should be applied to a TSC concept. As such, the normal conditions of storage definition for cask design basis should include a dry, inert or nitrogen atmosphere with maximum rod temperatures in the range of 300-400°C for internal conditions. In addition, the relative components of the 10 CFR 71 normal conditions of transport definition should be used for external environmental conditions.

RESULTS AND CONCLUSIONS

From our analyses, we conclude that a TSC system can be developed that contains a specific mix of design, operation, validation monitoring, and pre-shipment functional assessments for transport reliability comparable to that for existing transport systems. The major concerns, in-storage deterioration and unanticipated in-storage conditions, are the most crucial because they could involve undefined processes that act over long times. Further, the effects are not necessarily generic and can affect one assembly, one cask, or all casks unless interior environments are controlled. Another concern is the extent of current data on material properties as functions of aging and exposure to various storage environments. Our review indicated no particular deterioration problems for some materials under expected conditions; however, unanticipated conditions were not addressed. Further, the potential for deterioration of mechanically or metallurgically joined components (e.g., bolted, welded, brazed parts) was not addressed. Therefore, it is clear that: (1) expected conditions must prevail during the storage period and the environment must be monitored to detect unexpected conditions; and (2) some initial design assumptions regarding the behavior of other components and materials under expected conditions may have to be validated using a control cask approach. An assessment of this type for consumable components under expected service conditions is identical to that used for similar transport cask components.

Pre-transport functional evaluations of the criticality, shielding, containment, and heat removal capabilities of a TSC appear necessary. These assessments may require specific measurements or an integration of monitored data. The frequency (once) yields pre-transport reliability comparable to that for a TOC immediately following a periodic maintenance evaluation. The key to successful implementation of this concept is to ensure that whatever the assessment method used, its reliability for failure detection must meet or exceed methods currently in use (or expected to be in use in the future) for TOC systems. Specific guidelines and uniform procedures for pre-transport evaluations must ultimately be developed.

One other concern, record-keeping and data processing, is an administrative issue that mainly affects any utility using TSCs. The ultimate receiver also has a vested interest. The notion of reviewing as much as 40 years of monitoring records before determining if a cask is fit for transport seems rather burdensome. With respect to the fuel, however, the burden is no different than that for all fuel in storage. Similar requirements exist regarding shipment, maintenance, and fabrication records for transport casks whose service lifetimes could be quite long. Thus, some procedures and practices are in place which can be adapted for TSCs.

In summary, while a TSC concept is feasible, some remaining technical issues and uncertainties must be resolved. A design and operational process has been developed which can lead to defensible conclusions regarding the transportability of a TSC after long term storage. The process will likely involve universal cask monitoring, evaluations of control casks, and extensive pre-transport functional evaluations. Some validation monitoring of the behavior of various cask materials and components may also be required to verify design basis assumptions because specific data for some materials and components will be sparse.

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