DEPLETED URANIUM DIOXIDE–STEEL CERMETS FOR SPENT-NUCLEAR-FUEL MULTIPURPOSE CASKS

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ABSTRACT

An alternative spent nuclear fuel (SNF) management system is proposed for the U.S. Department of Energy and utility SNF that uses multipurpose casks made of a depleted uranium dioxide (DUO_2)-steel cermet. The proposed Yucca Mountain repository is designed for SNF received in transport casks. The SNF assemblies or SNF in baskets are transferred to repository waste packages that, in turn, are emplaced in the repository. The knowledge gained in the repository licensing process, potential new requirements to address issues such as terrorism, and new technologies create the option of an improved SNF disposal system as a second phase of repository development. The proposed system uses a multipurpose cask, in which the cask is loaded with SNF at the reactor. The sealed cask is then used for storage, transport, and ultimate disposal of the SNF. Multiple handling of SNF is avoided. Overpacks are used to address conflicting requirements between storage of short-cooled SNF and disposal. The DUO_2-steel cermet is a new material that is an enabling technology to maximize cask capacity (improved economics), provide added protection against assault, and improve repository performance.

INTRODUCTION

Multipurpose casks [1], constructed of depleted uranium dioxide (DUO_2)-steel cermets (Fig. 1), are proposed for the management of spent nuclear fuel (SNF). The cask shells would be constructed of a cermet of DUO_2 embedded in the steel, which, in turn, would be contained between clean layers of steel. Multipurpose cermet casks (Fig. 2) would be loaded with SNF at the reactor or at interim storage locations. These casks would then be used for interim storage, long-term storage, transport, and final geological disposal—with no additional handling of the SNF itself.

Multipurpose casks have potentially large advantages over the current system where SNF is (1) transferred from the reactor and stored in pools, (2) transferred to storage casks, (3) loaded into transport casks for shipment to the repository, and (4) transferred at the repository to disposal casks and placed in the repository. The recent concerns about terrorism have increased interest in multipurpose casks because of their resistance to assault compared to many other SNF management systems. However, there have been two limitations. First, the design of a multipurpose cask system requires a detailed understanding of all requirements: storage, transport, and disposal. Storage and transport requirements are understood but there are significant uncertainties associated with repository requirements. Within the next decade, the design and licensing of the proposed Yucca Mountain (YM) repository will be undertaken. This will result in a full understanding of all system requirements and enable the design of a multipurpose cask system for an improved, second phase of repository operation. Second, it is technically difficult to design a multipurpose cask that can meet all the requirements.

A series of studies and evaluations [1–4] were undertaken to examine (1) a new type of multipurpose cask system using new materials for cask construction and (2) a new design to fully utilize the advantages of the new materials to meet the multiple cask requirements. The DUO_2-steel cermet is potentially an enabling technology to create a practical multipurpose cask system. The results of this analysis (i.e., the system description) are reported herein.

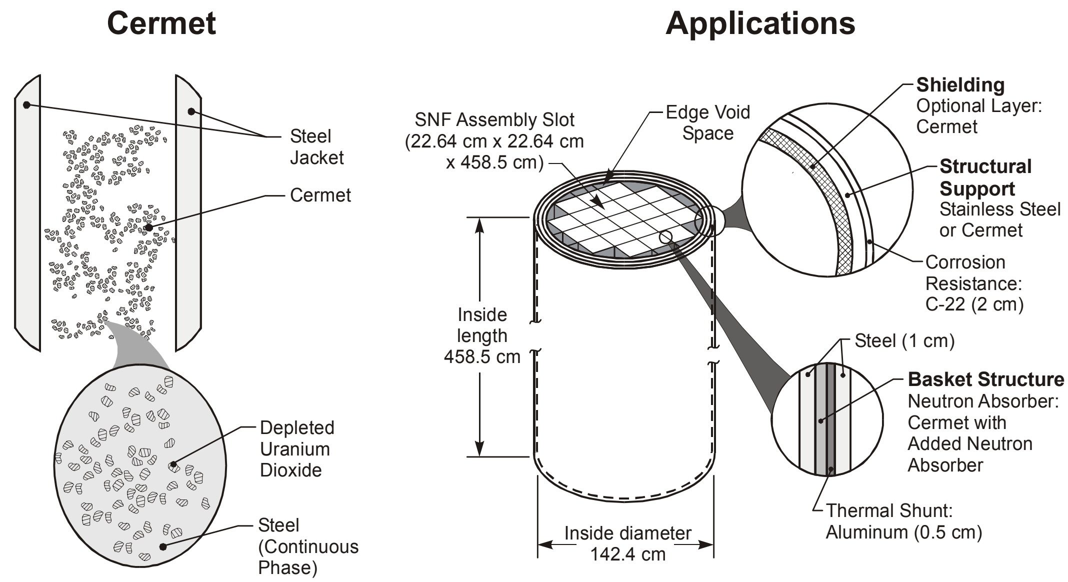

Fig. 1. Cermet Cask Construction.

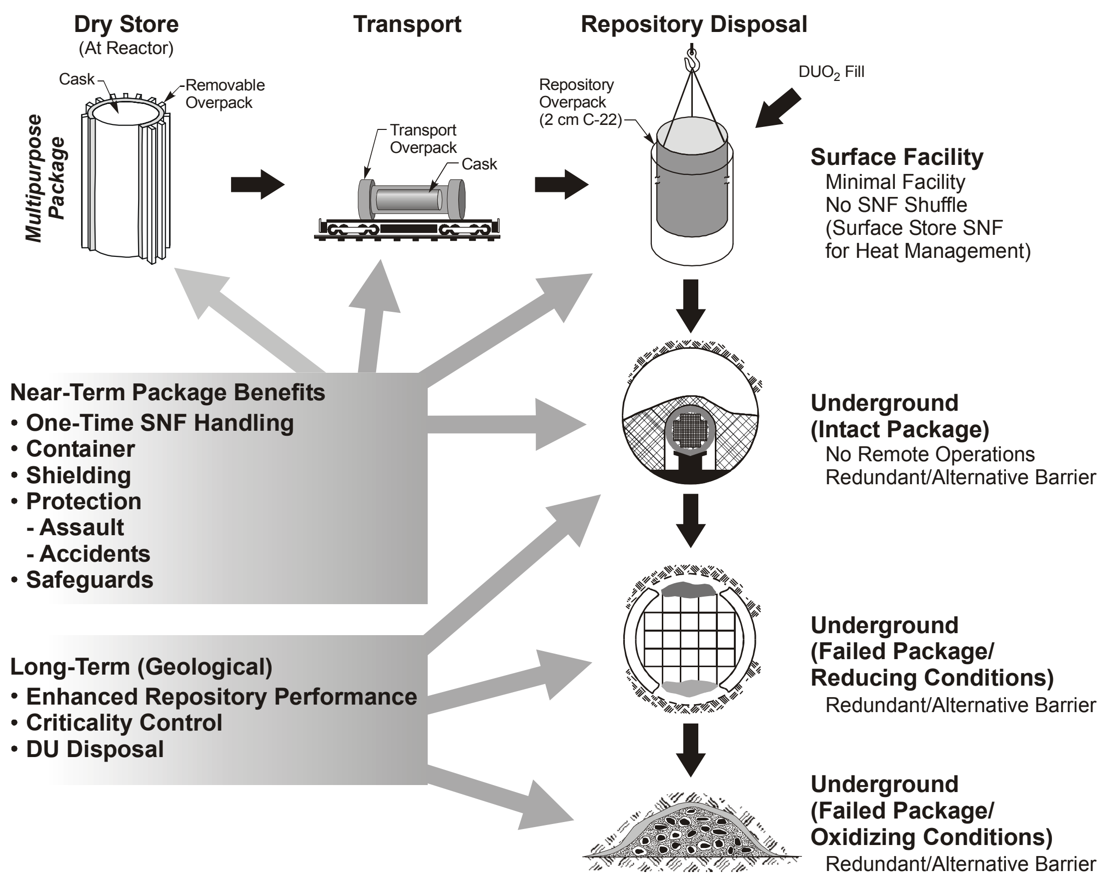

Fig. 2. Multipurpose Cask SNF Management System.

SYSTEM DESCRIPTION

The proposed system (Fig. 2) contains a multipurpose cask, storage overpack, transportation overpack, and repository overpack. The overpacks address conflicting storage and disposal requirements that cannot be easily met by the multipurpose cask. The multipurpose cask is constructed of a DUO_2-steel cermet. Because UO_2-steel cermets were originally developed as a type of test reactor fuel, the properties of such cermets are well understood. For the work described herein, the multipurpose cask [1] has the same capacity as the proposed waste package (WP) for YM with 21-pressurized-water-reactor SNF assemblies. The multipurpose cask cermet walls (25 cm thick) are assumed to be 50 vol % DUO_2 (36,900 kg) and 50 vol % steel (26,500 kg).

Multipurpose Cask

The multipurpose cask performs several functions: (1) serving as a handling package for SNF from the reactor to the repository, (2) providing primary radiation shielding, (3) offering physical protection against assault and accidents, and (4) functioning as a sealed safeguards package. Within this system, the DUO_2-cermet cask provides several unique benefits.

Shielding. The DUO_2-steel cermets may be the highest-performance shielding material [1] that can meet all requirements. Cermets provide better gamma shielding than steel because DUO_2 (10.9 g/cm^3) has a higher density than steel (7.8 g/cm^3). Because of the high oxygen content associated with the DUO_2, which moderates neutrons, cermets also have better neutron shielding capabilities than steel. The cermet would include a neutron absorber such as gadolinium oxide for efficient absorption of thermal neutrons. The more-efficient shielding materials are prohibited by one or more of the storage, transport, or disposal criteria. An examination of these criteria eliminates (1) chemically reactive materials, such as uranium metal [5]; (2) materials that may impact repository performance, such as concretes or organics—the traditional materials for neutron shielding; (3) high-cost materials, such as tungsten; and (4) Resource Conservation and Recovery Act metals, such as lead.

High-performance shielding materials minimize cask weight and wall thickness [1]; in turn, this maximizes cask capacity for any given set of handling constraints in storage, during transport, and in the repository. The greater the SNF capacity of each cask, the fewer casks that must be built and handled. This has a major impact on the economic viability of multipurpose casks. High-performance shielding that minimizes cask wall thickness allows larger capacity casks to be used at reactors and minimizes repository tunnel diameters. High-performance shielding lowers cask weight for any given SNF capacity. Cask circumference increases with cask diameter. Consequently, there is more mass in each centimeter of shielding from the inside to the outside of the cask wall. Wall thickness should be minimized.

The proposed YM WP is an unshielded package. Shielded WPs offer operational advantages in WP emplacement, inspection, and backfill of disposal drifts. No remote operations are required underground. Shielded WPs are more expensive than unshielded WPs and require heaver emplacement equipment. However, if shielded multipurpose casks are used for storage and transport, the incremental costs to use the same casks as part of the WP may be significantly less than construction of separate WPs. The system characteristics determine the economics.

SNF handling. The multipurpose cask system eliminates most SNF handling operations and costs. Except for the initial SNF loading, all operations are contact-handled (not remote) operations. Where protection against aircraft accidents and assault is required (such as in Germany), the cask provides the barrier and avoids the need for handling operations within aircraft-resistant containment structures (see below).

Multipurpose casks simplify repository surface operations. To ensure long-term repository performance, decay-heat limits are imposed on each WP. WP heat loads at the proposed YM repository are to be controlled by selection of hot and cold SNF for each WP, which involves sorting and handling of SNF. In a multipurpose cask system, casks with high heat loads would be stored on the surface at the repository until the WP decay heat has decreased to the allowable repository limit. Storage, not SNF sorting and handling, would be used to control WP heat loads.

Assault and accident resistance. Because of their intrinsic characteristics, multipurpose casks have high resistance to assault and accidents.

- Inventory. The inventory of each cask is limited. In a severe accident or terrorist event, this limits the consequences of any single incident, which may offer significant advantages.

- Passive cooling. Because of the limited inventory of SNF, and, thus the limited decay heat load, casks are cooled by using passive cooling techniques. Avoiding the use of active cooling systems, such as are used in SNF pools, offers a major advantage.

- Fire. In aircraft collisions and some other types of accidents, fire is a primary threat. The high thermal inertia of a cask provides significant protection against very high external heat fluxes experienced over a finite (or short) period of time. The modular characteristics of casks make it relatively easy to limit the duration of any fire. In refineries and other facilities with the potential for long-duration fires, the ground is (1) sloped to allow liquid fuels to drain away from equipment to burn pits or (2) covered with crushed rock to allow drainage of fuel underground (away from air, thus extinguishing the fire). This practice limits the duration and intensity of any fire near sensitive equipment. The same strategy may be used when multipurpose casks are stored outside.

- Physical protection. The thick walls of a cask provide significant protection against aircraft impacts. In Germany, metal casks have been successfully tested against aircraft collisions by firing 1-tonne heavy metal poles (the size of jet engine rotors—the strongest and most damaging component in an aircraft) into SNF casks at 300 m/s [6]. Limited tests have been conducted using military weapons with variable results [7]. Casks have a special property that buildings do not share. Casks do not have foundations and thus will move under high-impact loadings. This process dissipates the energy in severe events and makes it more difficult to destroy a cask than to destroy a building of the same wall structure and thickness.

  Tank armor, bank vaults, and other secure structures are designed with hard (ceramic) and ductile materials (metals) to maximize resistance to a wide variety of threats: high-speed long-rod projectiles (military shells and tornado-driven poles), explosive shape charges, high temperatures (thermite bombs and fires), and cutting tools. Many types of armor are cermets. However, to minimize weight and avoid issues associated with radioactive materials, DUO_2 is not generally considered for such applications. The potential exists to increase cask assault resistance by designing the DUO_2-steel cermet to function as armor while meeting the other performance requirements.

Safeguards and physical protection. The multipurpose casks (1) minimize the number of times that SNF is handled (i.e., making it possible to avoid separate transfer of SNF from the pool, to a storage cask, to a transport casks, and then to a disposal cask), (2) minimize the potential for diversion and theft because of their large size and weight, (3) provide strong physical protection compared with many other SNF storage methods, and (4) simplify tracking of the SNF. These benefits may be particularly advantageous in managing highly enriched SNF as well as that of foreign origin.

Enhanced repository performance. The cermet can enhance repository performance with the potential for reducing the need for other engineered barriers such as the proposed titanium drip shield [8, 9]. The initial performance of the WP, while the corrosion-resistant outer C-22 is intact, is identical to that of the current WP. After WP failure, however, the cermet [4] may delay SNF degradation for tens to hundreds of thousands of years. Most of the fission products and actinides in SNF are incorporated into the UO_2 crystal structure and cannot be released until the UO_2 is oxidized [10, 11]. The proposed YM repository has oxidizing groundwater; thus, in the current system, SNF oxidation occurs shortly after WP failure. The cermet WP changes this behavior. When groundwater enters a failed cermet WP, the oxygen first oxidizes the iron in the cermet; then the high-surface-area DUO_2 particulates released by iron oxidation; and, last, the SNF UO_2 that is partly protected by cladding. Because the oxygen preferentially consumes the cermet, SNF degradation is delayed.

The DUO_2 provides a unique groundwater barrier that operates to protect SNF under all conditions. The performance of all other proposed engineered barriers depends upon the assumption that future conditions will be somewhat similar to current conditions. Corrosion-resistant materials such as C-22 are highly corrosion resistant under some conditions but not under others. The DUO_2 is unique. Although it has the same chemical form as the uranium in the SNF, as the cermet degrades, it is released from the iron as a particulate with a high surface area. Whatever the groundwater, it will attack the DUO_2 before the SNF UO_2. The DUO_2 is a sacrificial material under all conditions. Associated with this barrier is the partial or full saturation of the groundwater in the WP with DU. In a uranium saturated groundwater environment, no more uranium can be dissolved.

After the cermet is oxidized, it provides some additional delays to radionuclide releases. The oxidized products of the cermet are lower-density materials that fill void spaces and tend to block fluid (gas or liquid) flow. The oxidized products of iron and uranium have significant sorption capabilities for many fission products and some actinides.

The DUO_2 cermet [3] provides an alternative strategy for repository criticality control that reduces constraints on the quantities of fissile materials in any WP. SNF contains many fissile materials. Assessments indicate that most of these fissile isotopes (such as ^{239}Pu) will decay to fissile uranium isotopes before transport from the degraded WP. The fissile uranium isotopes physically mix and then isotopically mix with the DU. Nuclear criticality is prevented by the process of isotopic dilution. For high-enriched SNF, there is also the option of adding DUO_2 fill to the void spaces within the WP to further dilute fissile uranium isotopes [2].

In the context of repository performance, there are two methods to add DUO_2 to the WP: using a cermet WP or filling the void spaces in the WP with DUO_2 particulates [2]. Either or both options can be adopted. This paper addresses only the cermet option. Cermets have the advantage that the DUO_2 is embedded in steel and thus invisible to operations. If particulate fill is used, it would be added at the repository just before emplacement.

Dry Storage Overpack

Cermets may enable higher capacity SNF casks for given weight and size constraints. However more SNF implies more decay heat. Furthermore, casks should accept relatively short-cooled SNF to minimize the SNF inventory in the SNF pool. However short-cooled SNF has higher levels of radiation and decay heat than aged fuel. A removable overpack for the cask can provide added shielding and cooling while the SNF cools.

Conflicting design requirements apply to high-capacity cask storage of short-cooled SNF and disposal of SNF. In storage, the primary design constraint is the need to avoid high temperatures, which would degrade the SNF. The storage cask requires a high ratio of surface area to volume (small casks or fins) to dissipate heat. For disposal, the primary design constraint is to ensure long-term WP integrity (decay heat levels are low). The WP should have a low ratio of surface area to volume to minimize (1) interactions between groundwater and the WP and (2) the cost of expensive corrosion-resistant materials. This implies a bare cylinder with smooth surfaces. The use of a removable overpack during storage is a method to resolve these conflicting performance requirements.

The overpack minimizes cask size and weight by providing radiation shielding not required for the cooler SNF during transport and disposal. The shielding requirements for short-cooled SNF are high because of two factors: (1) the high radiation levels from short-cooled SNF and (2) the added requirements for array storage. In large storage arrays, the sum of the radiation fields from each cask results in significantly greater shielding requirements than those required for a single cask during operations.

The overpack has either dry fins or wet fins. The largest temperature drops within the cask are (1) from the SNF through the basket to the internal cask wall and (2) from the external cask wall to the air. The temperature drop across the cask wall itself is small. The temperature drop to the air can be drastically reduced by the use of fins, particularly liquid-filled fins that allow efficient transfer of heat from the cask wall to high-surface-area fins. This is the same approach that is used in most utility electrical transformers. Many alternative coolants can be used, including water with antifreeze and corrosion inhibitors. Each fin is separate from the others; thus, damage to any individual fin does not significantly degrade the total system performance. Liquid-cooled fins provide improved fire resistance because of the large quantities of heat required to boil off the liquids before the cask heats up.

SNF temperatures must be controlled to avoid long-term SNF degradation. The degradation is a function of the time and temperature. The overpack shielding requirements are controlled by the need to reduce long-term radiation levels in the area. As a consequence, the overpack is required for long-term storage but not for short-term accident or assault conditions, where repair is possible within a limited time period. The multipurpose cask meets the severe-event requirements and thus allows greater freedom in the design of the overpack.

Transport Overpack

The transport overpack provides the added protection required for transport. The reactor and repository sites have limited access and tight controls; however, such conditions do not exist on public roads and railroads. Most of the requirements for the transport overpack are directly or indirectly a result of this difference.

Disposal Overpack

The proposed YM WP has an inner container for the SNF and an outer container of a corrosion resistant alloy (2 cm of C-22). The inner container provides the structural support for the corrosion-resistant outer overpack. In a multipurpose cask system, the multipurpose cask replaces the inner container. The outer container, which remains unchanged, is placed over the multipurpose cask at the repository.

DU DISPOSAL

The world inventory of DU is approximately one million tons—half of which is located in the United States. There are major advantages in using the DU to manufacture multipurpose casks. First, DU is a long-lived, chemically toxic, radioactive (300-to-500 nCi/g) material. Disposal in a repository ensures its safe isolation from humans. Because of the identical geochemical behavior of all uranium isotopes, DU can be safely co-disposed of with SNF [5, 11]. Second, there are strategic benefits. At the current time, uranium resources are sufficient to meet all demands. Sometime in the future, however, it may be necessary to process SNF to recover fissile materials and recycle DU into advanced reactors. Use of DU in SNF WPs provides a means of safely disposing of both materials as well as collocating them should future generations require these fissile and fertile materials.

ECONOMICS

Economics determines multipurpose cask system viability. The economics depends upon: future reactor SNF storage requirements—including resistance to assault (if dry casks become the preferred storage method, the incremental costs of multipurpose storage casks will be low); the need to minimize repository surface facilities and operations, such as the sorting of SNF to control decay heat load in each WP; the potential of a DUO_2 cermet to replace one or more repository engineered barriers; the SNF capacity of a cermet multipurpose cask, the cost of DU disposal if it is not beneficially used; and the cost of cermet manufacture. Preliminary analysis suggests potentially large economic benefits, but further studies are required before there can be high confidence in the results.

TECHNICAL ISSUES

As a new material, a DUO_2-steel cermet has the potential to enhance the performance of a multipurpose cask system. Additional research on cermets is required. Research is also required on other technologies to fully exploit the potential benefits of cermets.

Repository performance. Although DUO_2 improves repository performance, the magnitude of the benefits is not well quantified. If this can be better quantified, it may be possible to use the cermet to replace expensive engineered barriers such as the titanium drip shield [9]. While the effects of maintaining a chemically reducing environment in a WP have been investigated in Europe [10, 11], this potential benefit has not been examined in depth in the context of the oxidizing environment of YM. Similarly, the potential benefits of local saturation of the WP environment with DU to suppress SNF UO_2 dissolution have received limited attention.

Cermet design and manufacture. Nonnuclear cermets are manufactured inexpensively in large volumes; but, UO_2-steel cermets have been manufactured only in small quantities. Technologies [1] for low-cost production methods must be adopted for DUO_2-steel cermets.

Cask basket design. Although strong economic and security incentives exist to load short-cooled SNF into large, full-size multipurpose casks, there are two constraints. First, such a practice requires efficient methods to limit SNF temperatures. With the adoption of cooling jackets, the primary resistance to heat transfer in a cask is from the SNF to the inner cask wall. Second, neutron shielding becomes a limiting factor for some types of high-burnup SNF. Cermets provide excellent gamma shielding but are less effective neutron shields. Cask-loading strategies to minimize shielding put the highest-burnup SNF in the middle of the cask, but this placement increases the difficulty in controlling peak SNF temperatures.

Ongoing research indicates that the use of directional graphite slabs as thermal shunts in the SNF basket structure may address both issues. Directional graphite has a high thermal conductivity (400 $W/cm^{3}\cdot{}^{o}C$), which allows efficient conduction of heat from the center of the SNF basket to the inner cask wall. Graphite also slows down fast neutrons which, in turn, reduces neutron shielding requirements. Graphite can be manufactured to incorporate neutron absorbers such as gadolinium. The graphite in the basket would replace (1) the aluminum sheets currently used as thermal shunts and (2) the neutron absorbers. Like aluminum and neutron absorber plates, the graphite would be sandwiched between steel sheets to form the basket structure.

CONCLUSIONS

The proposed YM repository system is being designed to accept existing SNF from DOE and utilities that is stored in a variety of systems. However, significant future quantities of SNF are expected and requirements for SNF management are changing. The licensing process will define repository requirements. These factors enable the design of an advanced SNF management system as a second phase of repository operation. A DUO_2-steel multipurpose cask system may offer major long-term advantages as a second-generation system. The viability depends upon the cask design and the system design.

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