Manufacturing and Economic Studies for DUO_2-Steel Cermet Spent Fuel Casks

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Abstract ─ *The use of depleted uranium dioxide (DUO_2)–steel cermets to construct spent nuclear fuel (SNF) casks for storage, transportation, and disposal is proposed. The use of cermets, which consist of ceramic particles embedded in contiguous steel, is a method to incorporate brittle ceramics [DUO_2, aluminium oxide (Al_2O_3), etc.] with highly desirable properties into a strong ductile metal matrix with a high thermal conductivity, thus combining the best properties of both materials. Potential benefits include greater SNF capacity for the same size or weight of cask, greater resistance to assault, improved repository performance, disposal of excess DU, and an integrated open fuel cycle. The practical question is whether such casks can be economically manufactured. Two new fabrication methods have been partly developed that may provide economic methods for cermet cask fabrication. The results of the initial manufacturing and costing studies are described for the new Cermet Extrusion Section process. This initial assessment indicates that cermet casks can be fabricated and that the process has the potential to meet the required economic goals.*

I. INTRODUCTION

Spent nuclear fuel (SNF) casks are required for storage, transport, and disposal. The casks may be designed for single or for multiple applications. [1] The functional requirements for an SNF cask include radiation shielding, cooling of the SNF to limit its peak temperatures, physical protection, and—for waste packages (WPs)—delaying the degradation of SNF over long periods of time. The cask may contain the individual SNF assemblies or canisters that contain multiple SNF assemblies. For example, in the United States repository planning includes the development of a transportation, aging, and disposal (TAD) canister system. In such a system, the cask would contain the TAD canister.

Meeting these requirements economically is complicated by other constraints. Handling facilities at the reactor restrict the weight of the cask to ~100 tons. The physical size is limited by facility constraints such as door openings at the reactor and by rail shipping requirements. Changing requirements (such as the need for better physical protection, higher-burnup SNF, longer-term storage, and repository disposal) have created strong incentives to design better casks.

SNF cask performance is ultimately limited by the performance of cask materials of construction. The outstanding performance of cermets follows from their intrinsic characteristic: the encapsulation of *variable* quantities of different ceramic particulates into a strong continuous high-integrity, high-thermal-conductivity ductile metal matrix. The mixture is optimized to meet specific requirements. The use of depleted uranium dioxide (DUO_2)-steel cermet casks was not previously investigated because (1) depleted uranium (DU) has been considered for disposal only in the last decade and (2) it was not evident that such casks could be fabricated. However, DU is now available and new fabrication techniques have been identified; thus, there is a strong incentive to examine the use of cermet casks. In the United States, DU from the enrichment plants is stored in the form of depleted uranium hexafluoride (DUF_6), a toxic, chemically reactive solid with a high vapor pressure. Chemical conversion facilities are under construction to convert this reactive chemical to relatively inert uranium oxides for disposal. This paper describes (1) the characteristics and benefits of a DUO_2-steel cermet cask, (2) fabrication options, (3) initial costing studies, and (4) conclusions.

II. CHARACTERISTICS AND BENEFITS OF CERMET CASKS

Figure 1 shows a cermet cask design. Steel is selected as the continuous metal phase in the cermet because of its low cost, high strength, and good thermal conductivity. The cermet is clad in steel to provide a clean outer layer to allow easy decontamination of the cask during normal operations.

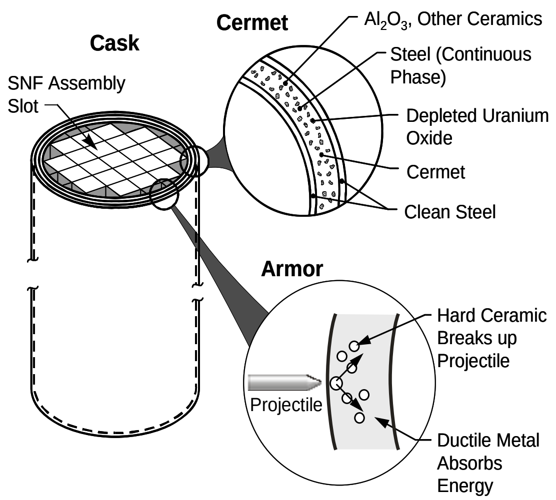

Fig. 1. Design of cermet cask.

The functional requirements of the cask define those for the cermet fabrication process. A series of studies have shown the potential for major improvements in cask design via the use of DUO_2-steel cermets. The potential gains from using this material of construction include the following:

- *Cask capacity*. A DUO_2-steel cermet has better radiation shielding characteristics than traditional materials such as steel.[2] The use of a cermet increases the number of SNF assemblies per cask for a given total gross cask weight limit or maximum allowable diameter.

- *Physical protection*. Cermets are a traditional material used in tank armor and in various cutting tools. Security concerns after 9-11 have resulted in the reevaluation of security requirements.[3]

- *Repository performance*. In a repository, the DUO_2 cermet may improve repository performance by multiple mechanisms.

  – *Optimized geochemical environment*. In a cermet WP, the ratio of DUO_2, iron, and other components can be adjusted to maximize WP performance[4] by (1) slowing the degradation of the UO_2 in the SNF and thus the release of radionuclides from the SNF, (2) slowing the movement of groundwater through the degraded WP after initial failure, and (3) slowing the dissolution of fission products and actinides.

  – *Geochemical trap*. Until the SNF UO_2 is destroyed, the radionuclides in the SNF are trapped. In this context, the DUO_2 plays a unique role. It has the same chemical behavior as the UO_2 in SNF. If the SNF is wrapped in the DUO_2, the DUO_2 acts as a sacrificial material to preserve the SNF UO_2. As the only compound with the same chemical behavior as SNF UO_2, DUO_2 is the only compound that can protect SNF UO_2 against all types of external chemical degradation mechanisms until it is consumed.[5] Other sacrificial materials can protect against a specific degradation mechanisms but not all such mechanisms.

  – *Neptunium sorption*. Neptunium is the controlling isotope in the performance assessment for the Yucca Mountain repository. Preliminary experimental data[6] indicate that DU retards the transport of neptunium to the environment.

  – *Nuclear criticality*. The use of DUO_2 reduces the potential for long-term repository criticality by isotopically diluting the fissile uranium isotopes to lower enrichment levels.[5]

- *Disposal of DUO_2*. DU is a by-product of the enrichment of natural uranium to produce enriched uranium for light-water reactors. Approximately a million tons of DUO_2 exists in storage worldwide with no identified large-scale uses. This application could use most of this inventory and avoid treating this material as a waste.

- *Unified open fuel cycle and optional closed fuel cycle*. The open nuclear fuel cycle generates two long-lived wastes: SNF and DU. Codisposal creates a single unified waste management strategy. If, in the future, the decision is made to go to a closed fuel cycle, the two nuclear materials required for this type of fuel cycle (SNF and DU) are collocated.

III. FABRICATION OPTIONS

Cermets are materials of choice for use in drill bits, armor, brake disks, and other extreme environments. The very properties that make these materials so useful also make them difficult to fabricate. Cermets are difficult to machine and difficult to weld in thick sections. The commercial viability of a DUO_2-steel cermet cask strongly depends upon the economics of cask fabrication. Two powder-metallurgy fabrication methods are being developed to fabricate cermet casks without machining or welding of the cermet.[7]

In each process, a mixture of iron and ceramic powders is ultimately converted into a high-integrity SNF cask. The recently patented[8] Forge Cermet Cylinder (FCC) process produces the cylindrical cask body in a near-final form as a single piece. The FCC process minimizes the number of processing steps and maximizes cermet performance; however, large equipment is required for cask fabrication.

The Cermet Extrusion Section (CES) process produces extruded cermet pieces that are then assembled into the cask body. Compared with the FCC process, the CES process offers several advantages: (1) it requires less research and development and thus is the near-term option, (2) the front-end capital investments are smaller, (3) the DUO_2 processing and contamination control are limited to a very small section of the manufacturing facility (a potential economic advantage), and (4) a more flexible manufacturing process that would reduce scrap. The potential disadvantage is that this fabrication process results in a lower-cermet-content cask. The CES process is described and assessed herein.

IV. CES CASK PROCESS

The CES process[4] produces extruded cermet sections that are then assembled into the cask body. Figure 2 shows the various pieces required to fabricate a cask, while Table I shows some of the key parameters for casks manufactured with 12, 24, 36, and 48 extruded sections per cask. Each section is curved to prevent radiation line-of-sight problems along seams in the cask and thus ensure uniform shielding characteristics.

For the manufacturing studies, the final ID of the cask is 68.75 in. and the OD is 80.75 in. The overall length of the cask is ~17 ft (204 in.). The total wall thickness of the cask is 6 in., of which the cermet sections comprise 5 in. and the steel shells on the ID and OD each comprise a thickness of 0.5 in. Compared with other cermet applications, an SNF cask is a very large component. For comparison, large tanks weight only 70 tons, of which the armor is only one component.

Figure 3 shows the steps in the manufacturing process. The CES process consists of the following steps, which are further described in Table I.

Powder preparation. Powder preparation consists of the blending of two (or possibly more) powders. For the steel powders obtained from commercial sources, the particle size distributions are typically broad and the diameters range from 10 up to 250 µm, with average particle sizes of 70 to 90 µm. These powders are easily handled with minimal dusting and are suitable for fabrication of the DUO_2 cermets. To maximize the packing density with the steel particles, the average particle size of the DUO_2 particles should be on the order of 10- to 13-µm diameter. Typical powder-processing additives would include additions of 1 wt % graphite to the steel powders. To aid in compaction, 0.75 wt % zinc stearate is added to act as a lubricant between the particles during compaction. The base-case cermet composition is a 50:50 vol % mixture of DUO_2 and steel powders, which corresponds to a 58.4:41.6 wt % ratio.

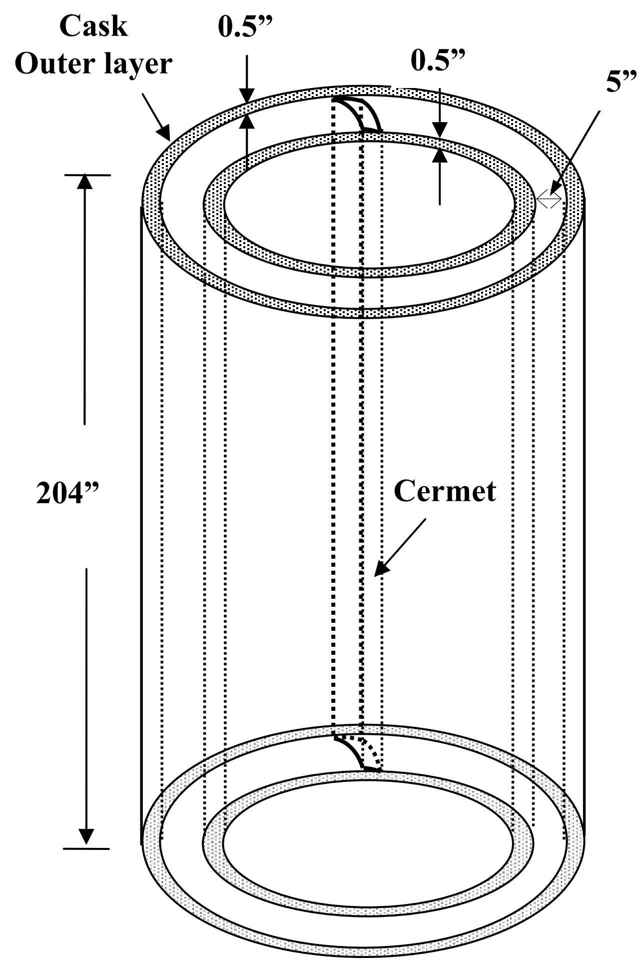

Fig. 2. CES cask with cermet segments between inner and outer cask shells.

TABLE I. CES Cask Design and Costing Parameters

No. of Cermet Sections	12	24	36	48
Billet/Extrusion Section Dimensions and Weights				
Initial Length[a] (in.)	39.5	39.5	39.5	39.5
Initial Diameter (in.)	33.48	23.67	19.33	16.74
Initial Wall Thickness (in.)	1	1	1	1
Initial Top and Bottom Thickness (in.)	2	2	2	2
Final Area ($in.^2$)	97.84	48.92	32.61	24.46
Final Length (in.)	234	234	234	234
Steel Preform Weight (lb)	2011	1207	906	742
Steel Powder Weight (lb)	2412	1143	731	529
DUO_2 Powder Weight (lb)	3385	1604	1026	742
Total Cermet Powder Weight (lb)	5797	2747	1757	1271
Total Section Weight (lb)	7807	3954	2663	2013
Cask Characteristics				
Total Weight Steel Powder (lb)	28,944	27,432	26,316	25,392
Total Weight DUO_2 (lb)	40,620	38,496	36,936	35,616
Total Weight Steel Preform (lb)	24,132	28,968	32,616	35,616
Total Weight Inner/Outer Shell (lb)	13,500	13,500	13,500	13,500
Total Cask Weight (lb)	107,196	108,396	109,368	110,124
Maximum Powder Die Pressure[b] (psi)	2,558	3,575	4,338	4,972
Total Powder Compaction Force[c] (lbs)	1,990,951	1,318,582	1,023,336	848,398
Fabrication Cost Components				
Steel Powder per Cask ($/Cask)	11,578	10,973	10,526	10,157
Steel in Sections per Cask ($/Cask)[d]	45,368	48,956	55,121	42,383
Cask shell ($/Cask)	16,050	16,050	16,050	16,050
Preform and Shell ($/Cask)	72,996	75,979	81,697	68,590
Consumables ($/Cask)	852	852	601	601
Extrusion				
Low Estimate per Section ($/Section)	16,875	11,250	7,500	5,000
Low Estimate ($/Cask)	202,500	270,000	270,000	240,000
High Estimate per Section ($/Section)	33,750	22,500	15,000	10,000
High Estimate ($/Cask)	405,000	540,000	540,000	480,000
Machining and Assembly				
Low Estimate per Section ($/Section.)	1,953	1,562	1,250	1,000
Low Estimate Cask ($/Cask)	23,437	37,500	45,000	48,000
High Estimate per Section ($/Section.)	3,906	3,125	2,500	2,000
High Estimate per Cask ($/Cask)	46,875	75,000	90,000	96,000
Total Cost: Low Estimate ($/Cask)	299,785	384,331	397,298	357,191
Total Cost: High Estimate ($/Cask)	525,722	691,830	712,298	645,190

[a]Based on obtaining a packing density of the DUO_2-steel powder compact of 62% TD.
[b] Maximum die pressures with 1018 steel plus safety factor.
[c]Total force needed for compaction (lb).
[d]Stronger steels required for compaction of the larger sections: 12 section used 4140 preform steel; 24 section used 1144 preform steel; and the 36 and 48 section used 1018 preform steel.

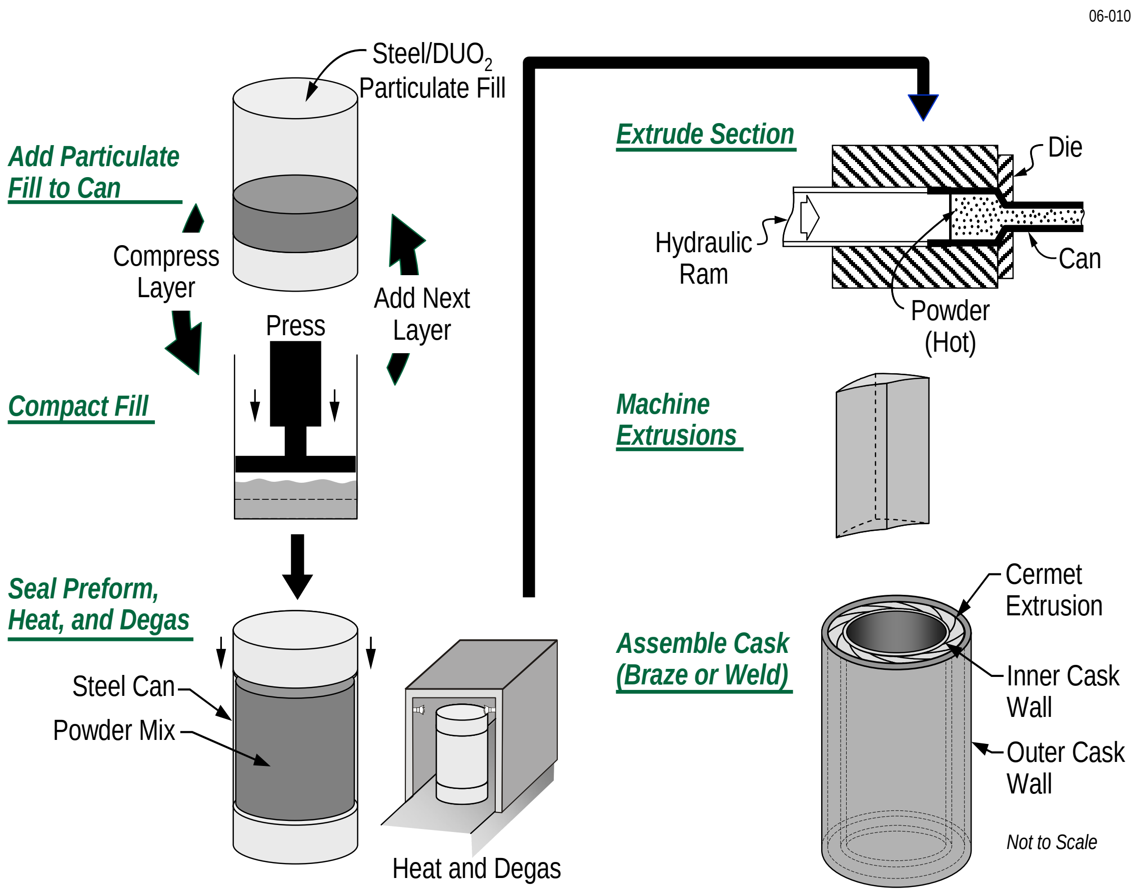

Fig. 3. Cermet Extrusion Section manufacturing process.

Preform fabrication. The preform consists of an open-ended steel cylinder with a wall thickness of ~1 in. and two thicker end caps. The preform becomes the outer clean steel surface that is extruded to form each cermet section. Plain or low-carbon steels are a reasonable choice because they are easy to form, bend, weld, and braze. The cylindrical steel preform with end caps weighs between 742 lb (48-section cask) and 2011 lb (12-section cask).

Preform filling. The preform is filled with a particulate mixture of DUO_2, other ceramics, and steel powder. This involves the cyclic operation of adding a layer of particulate mixture and then compacting that layer with a pressure of 5 ksi to a final thickness of ~1 in. This process is required to provide a relatively uniform, reasonably-dense green body to ensure proper operation of the extrusion process. In this case, about 35 pressings are required. The apparent density of the powder blend is ~35% of the theoretical density (TD), which is typical for powders. The height of the cermet powder compact within the cylinder is ~34.5 in. which assumes that each layer can be compacted to ~62% TD. Because of the need to achieve 5 ksi pressures during the powder pressing, different grade steels are needed for the different section designs. For the 12 section design, high-strength 4140 steel is needed and for the 24 section design lower-cost 1144 steel could be used. For the 36 and 48 section designs, 1018 or 1045 steel could be used.

Welding, heating, and gas evacuation. After the filling is completed, a steel cylinder top is welded to the preform. The preform is then evacuated while being heated, which decomposes the organic binders that must be removed before further processing. A typical binder burnout procedure requires a slow heatup of the part to ~500°C under vacuum to be sure all of the volatiles are removed.

Extrusion. The preform is heated and extruded at an ~9:1 area-reduction ratio to densify the cermet and produce the desired final cross section. The technology for high-temperature steel extrusion is a relatively recent development.

Machining. The extrusions must be machined to the final dimensions. All machining operations are performed on the external steel of the extruded piece, not on the internal cermet. This avoids the very difficult operations of welding or machining cermets.

Cask assembly. The extruded sections are placed between inner and outer steel cylinders that are the inner and outer surfaces of the final cask. The segments and steel cylinders are bonded together by a heat treatment or brazing.

The small size and low weight of the individual pieces minimize CES process equipment sizes and facility investments but requires additional steps to the fabrication process. Each of the cermet sections requires a full steel exterior for the extrusion process. Consequently, the greater the number of cermet sections used to manufacture the cask, the more steel that is located in the interior sections of the cask, thus reducing the fraction of the cask made of a cermet.

V. MANUFACTURING COSTS

Preliminary estimates of manufacturing costs have been developed (Table 1). It is assumed that the DUO_2 is provided at no cost. The steel powder is obtained from commercial sources. (Current prices are ~\$0.40/lb in 40,000-lb lots.) The steel components are fabricated of 1018 steel, a relatively low cost steel (\$1.19/lb) with sufficient strength. Small equipment is amortized over the fabrication of 200 casks. For activities where no contamination of equipment is envisioned (extrusion of the billets into the various sections, inspection of the extruded sections, machining to correct dimensions, assembly of the sections into cask preforms, and final heat treatment), outside toll fabricators are used.

Preliminary cask manufacturing costs are estimated to be between \$300,000 and \$700,000 per cask. The large cost uncertainties are primarily a consequence of uncertainties in the extrusion costs. Manufacturing studies, including the manufacture of prototype sections, may be required to provide better cost estimates. The extrusion of large steel components is a relatively new technology which implies significant uncertainties in estimating costs. However, it is also an area where experience and technological advancements are rapidly lowering costs.

The manufacturing cost is one of several inputs in determining cask economics. There are several other factors that are equally important. Because of the higher shielding performance of cermets, a cermet cask can carry more SNF assemblies for a given cask weight or size limit─a direct one-to-one cask comparison cannot be made. Many cask operations such as loading times, transport costs, and security costs are primarily per-cask costs; thus, there are large savings in reducing the number of casks. Because cermet casks make it possible to dispose of DU, any financial credit given for disposal of DU has a major impact. Last, requirements for repository performance or security can drastically alter the preferred economic option.

VI. CONCLUSIONS

A series of studies have been conducted to understand the advantages and disadvantages of DUO_2-steel cermet casks. The unique material properties of cermets imply superior technical performance relative to other materials of SNF cask construction. Manufacturing studies on cask fabrication using the CES process indicate technical feasibility and potentially favorable economics; however, there are two significant uncertainties: (1) the costs of extrusion, which are responsible for the large uncertainties in cask manufacturing costs; and (2) the maximum allowable ceramic (DUO_2) content of the cermet. A conservative DUO_2 content was chosen. Studies and prototype fabrication of cermet sections, using DUO_2 or a substitute such as hafnium oxide (HfO_2), which has similar properties, are required to reduce the uncertainties.

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