ALTERNATIVE MANUFACTURING METHODS FOR DEPLETED URANIUM DIOXIDE–STEEL CERMET SNF CASKS

Charles W. Forsberg
Oak Ridge National Laboratory*
P.O. Box 2008
Oak Ridge, Tennessee 37831-6179
Tel: (865) 574-6783; E-mail: forsbergcw@ornl.gov

Vinod K. Sikka
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831
Tel: (865) 574-5112; E-mail: sikkavk@ornl.gov

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Alternative Manufacturing Methods for
Depleted Uranium Dioxide-Steel Cermet SNF Casks

Charles W. Forsberg and Vinod K. Sikka
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6179
Tel: (865) 574-6783; E-mail: forsbergcw@ornl.gov

Abstract—*Cermets using depleted uranium dioxide and other ceramics embedded in a steel matrix are being investigated*[1-3] *as materials of construction for spent nuclear fuel storage, transport, and disposal casks, as well as for multipurpose cask bodies. Cermet cask performance (shielding thickness, resistance to assault, capacity for a given weight limit) has the potential to significantly exceed that of traditional materials. The viability issue is manufacturing costs. Alternative manufacturing methods were investigated: (1) casting of a ceramic particulate/molten-metal slurry and (2) powder metallurgy. A new (patent pending) powder metallurgy method for fabricating large casks was invented*[4] *that may result in low fabrication costs. The potential favorable economics are a result of (1) a process that produces a near-final-form cask that minimizes the number of processing steps and (2) the low cost of the starting materials.*

I. BACKGROUND

Cermets using depleted uranium dioxide (DUO_2) are being investigated[1-3] as a material of construction for spent nuclear fuel (SNF) storage, transport, and disposal casks, as well as multipurpose casks. The cermet (Fig. 1) consists of DUO_2 ceramic particulates and other particulates (graphite, silicon carbide, etc.), if needed, embedded in a steel matrix between two clean layers of steel.

Cermet SNF casks have the potential for very high performance compared with casks constructed of traditional materials. The material properties of cermets permit the construction of casks with greater capacity (more SNF assemblies per cask) for the same given weight and size constraints.

These excellent properties follow from the fundamental characteristic of a cermet: the ability to encapsulate variable quantities of different ceramic particulates into a high-integrity monolithic metal matrix. The ceramic components have outstanding properties to address specific cask requirements. The DU is a high-performance gamma-radiation shielding material. The oxygen, carbon, silicon and other additives provide enhanced neutron shielding by slowing and then capturing neutrons. However, these ceramics have poor physical properties (e.g., low thermal conductivity, low ductility), weaknesses that can be avoided by the use of a continuous metal matrix. With the proper choice of particle sizes and materials, the cermet can also provide higher resistance to assault and accidents than traditional materials. Many types of armor are made of cermets, in which the ceramic and metal components are selected to address different kinds of threats. Traditionally, cermets are used in very severe operating environments: (1) tank and vault armor, (2) brake shoes, (3) tool bits, and (4) nuclear fuel in some test reactors. Because UO_2 cermets have been used as nuclear fuels[1] and their properties are understood, there is reasonable confidence in the technical potential of cermet SNF casks.

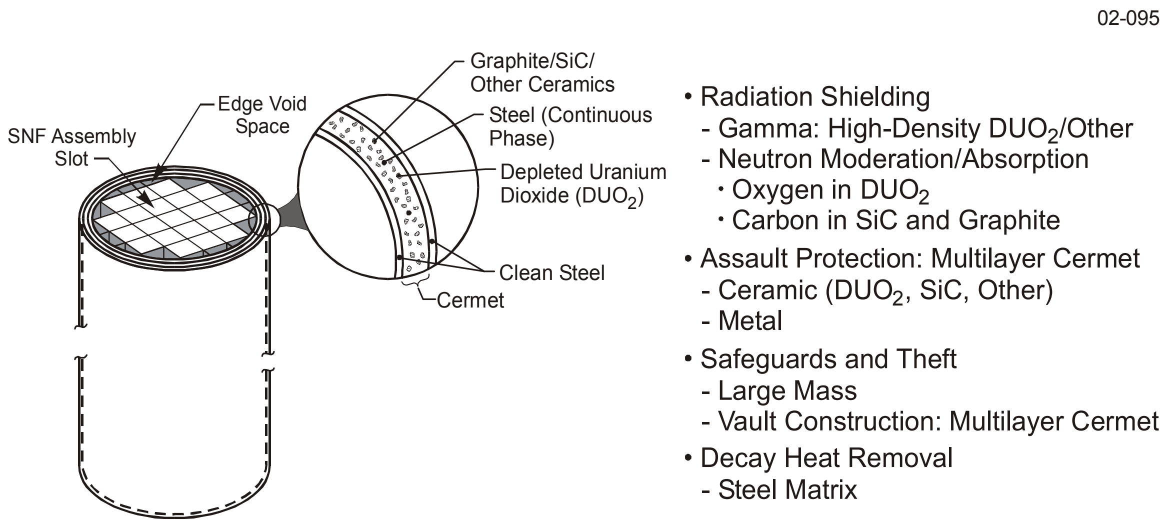

Fig. 1. Depleted uranium dioxide–steel spent nuclear fuel cask.

While the potential performance of cermets is outstanding, the viability of using such an advanced high-performance material depends upon developing low-cost reliable cask fabrication technologies. Technological complications exist. The forming and welding of cermets are very difficult. Consequently, production of the cermet material and fabrication of the cask body must be considered simultaneously. Alternative cermet cask fabrication technologies were examined in terms of (1) ability to fabricate cermet casks with desired properties and (2) costs. Two sets of fabrication technologies (Fig. 2) were identified: casting and powder metallurgy. UO_2 cermets have traditionally been produced by powder metallurgy methods. The casting method has not yet been demonstrated with UO_2.

II. CASTING

Many non-DUO_2 cermets are manufactured in large quantities by casting (i.e., adding solid ceramic particulates to a molten metal and transferring the resultant slurry to a mold to produce the final form). Casting is a traditional, low-cost method to produce large components.

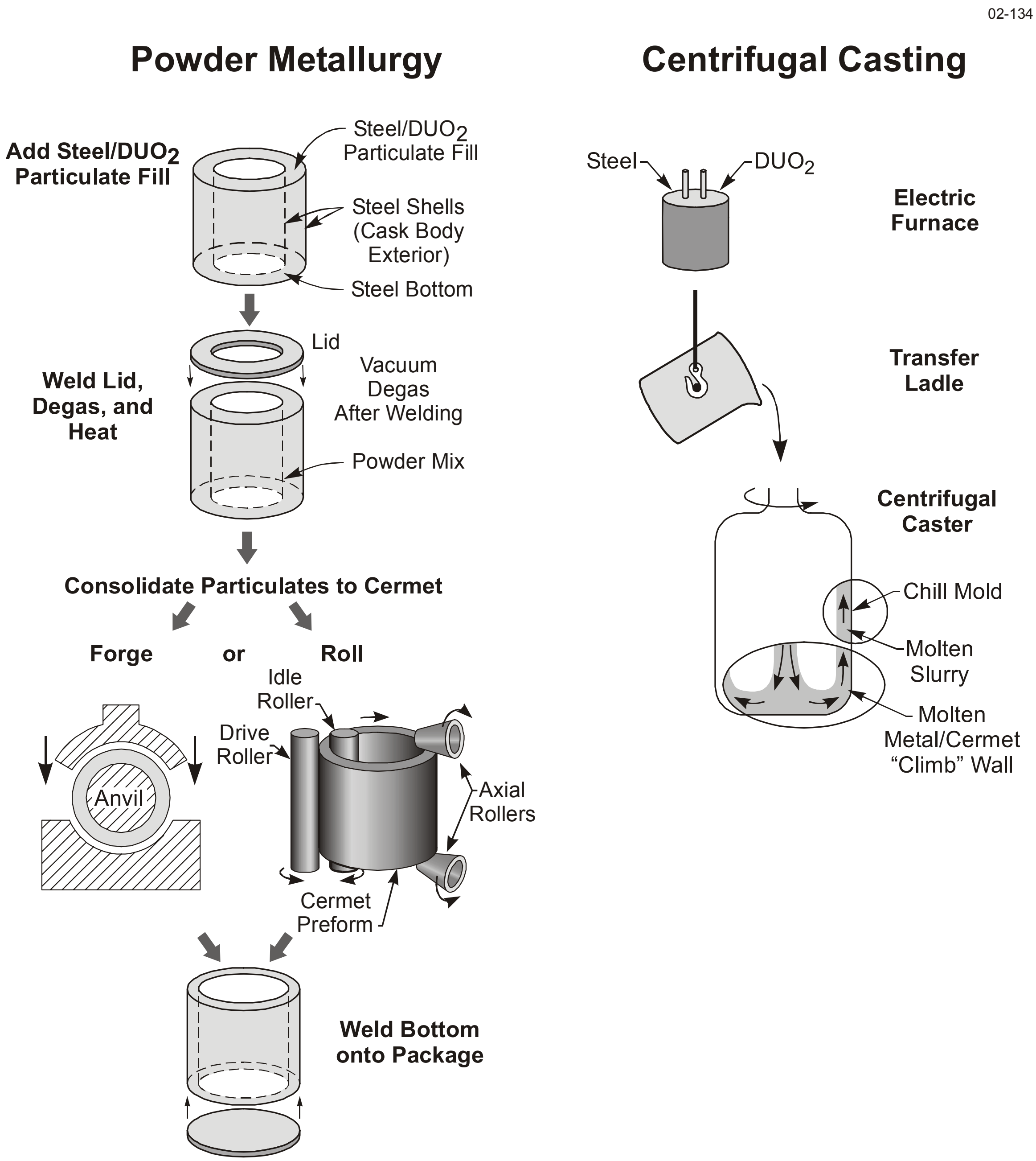

Fig. 2. Powder metallurgy and centrifugal casting cermet production methods.

There are three requirements for cermet casting: (1) the ceramic particulate must not chemically react with the metal, (2) the ceramic particulate must not melt or rapidly dissolve in the molten metal, and (3) the molten metal must wet the ceramic. While the higher-valence uranium oxides chemically react with iron and thus are not candidates for a cermet produced by casting, DUO_2 is thermodynamically stable in the presence of iron and similar materials. The melting point of UO_2 is more than 900EC higher than that of iron, and DUO_2 does not significantly dissolve in iron. However, the ability of metal alloys to wet DUO_2 has not been demonstrated. If the molten metal does not wet the ceramic, surface tension will cause voids in the final cermet and result in the loss of strength. If a molten metal does not naturally wet a ceramic, experience has shown that addition of small quantities of magnesium or similar metals to the melt usually enables such wetting to occur. Experiments are being planned to test the wetting of DUO_2 by various steels and to determine the need for alloy additives to improve wetability.

Three potential cermet casting techniques have been identified, each of which has specific advantages and disadvantages.

Infusion casting. With this method, the cask mold is filled with DUO_2 particulates. Molten metal is infused into the ceramic particulate bed, usually under vacuum conditions. Although this technique is used with small objects, it is unclear whether it could be used on large items such as SNF casks.

Traditional casting. Solid DUO_2 particulates can be added to molten steel and the resultant dispersion can then be poured into a stationary mold. Many non-DUO_2 cermets are made by this technique. The DUO_2 has a higher density than the molten steel; thus, DUO_2 particulates tend to go to the bottom of the mold. This may be prevented by one of two techniques. First, the temperature of the slurry can be carefully controlled to ensure that the slurry freezes before significant separation occurs. Alternatively, the DUO_2 particulate size can be controlled so that a relatively uniform particulate bed with steel in the void spaces is created, which then forms a cermet upon freezing. Although this casking technique is much simpler, the manufacturing method imposes two limits on the product: (1) only certain ratios of DUO_2 to steel can be produced, and (2) only simple cermets containing one ceramic are possible. If ceramic particulates with different densities are added to the slurry, they will separate in the casting operation.

Centrifugal casting. Solid DUO_2 particulates can be added to molten steel. In centrifugal casting (Fig. 2), the mold is rotated at ~400 rpm while the dispersion of DUO_2 particulates in molten steel is added to produce a cylindrical shell. This technology allows the pouring of multiple layers of metal or cermet, with time allowed for metal solidification between each pour; thus, the cermet can be encased in clean steel. Centrifugal casting generally provides a superior product because the high gravitational forces ensure the absence of porosity within the casting, full separation of any slag from the steel, and a uniform thickness.

III. POWDER METALLURGY

Uranium-dioxide cermet nuclear fuels have been successfully manufactured for many test reactors[1] using traditional powder metallurgical techniques. As a consequence, the properties and characteristics of such cermets are well understood. The traditional powder metallurgical technique involves (1) mixing the metal powders and ceramic particulates, (2) enclosing the mixture in some type of close-fitting metal box, (3) heating the mixture while removing the gases between the particulates by vacuum, and (4) compressing the box and mixture at high temperatures to create a monolithic matrix of metal that encapsulates ceramic particulates.

Powder metallurgical techniques can produce cermets made of materials that are normally considered to be incompatible because the forming process is below the melting points of the various components. The compression eliminates void spaces in the particulate bed, while the high temperature welds the metal particulates together. This approach, which is a well-understood manufacturing method, makes it possible to include other materials in the cermet to enhance its capabilities.

The production of a cask, however, presents special requirements: the manufacture of an annular object with weights up to 100 tons. Methods to manufacture a cermet of this size and geometry do not presently exist. While existing powder metallurgical fabrication methods could clearly be used successfully, such a process would involve assembly operations of smaller pieces of cermets into a large cask with associated cost and performance penalties. Consequently, a new manufacturing method (Fig. 2) has been invented[4] to fabricate such casks. While the fabrication technique is new, the cermet forming processes on a microscopic scale (temperatures, pressures, material compositions) are the same as those associated with the traditional processes. The new process consists of the following steps.

- *Preform fabrication*. A preform slightly larger than the final annular cask body is constructed of steel and serves as the outer layer of clean steel in the final cask. The preform consists of the inside, outside, and top surfaces of the cask body but excludes the cask bottom.

- *Preform filling*. The preform is filled with a particulate mixture of DUO_2, other ceramics, and steel powder. A schematic of the filling process is shown in Fig. 3. The upside-down cask preform is placed on a table that can be rotated. The fill machine particulate distribution heads are lowered to the bottom of the preform. As the table rotates, the fill machine (1) feeds particulate mixes [steel and ceramic particulates] to the preform in a continuous layer that is several centimeters deep, (2) compacts each layer as it placed in the preform, and (3) is withdrawn as the preform is filled with a continuous spiral particulate layer from the bottom of the preform to the top. Many rotations are required to fill the preform. The use of multiple particulate feed nozzles makes it possible to vary the composition of individual layers from the inside of the cask preform to the outside. The composition of the particulate mix can also be varied in the vertical direction. In fact, this design allows the fill machine to vary particulate composition throughout the entire preform. The compaction is to assure no movement of the particulate fill during subsequent handling operations. The gas composition within the preform is maintained under chemically reducing conditions to avoid oxidation of the steel powder.

- *Welding, heating, and gas evacuation*. After the preform is filled, an annular ring is welded to the preform to create a loaded, sealed annular preform. The preform is then evacuated while being heated, which removes gases in the void spaces in the particulate mixture and gases sorbed on the particulates.

- *Forging.* The preform is heated and compressed to (1) eliminate all void spaces and (2) weld the metal particles together to form a continuous, strong steel matrix containing various ceramic particulates. The compression is performed at high temperatures to (1) minimize the forces necessary to eliminate all voids in the particulate mixture and (2) rapidly weld the steel particulates into a solid matrix by solid-state diffusion. Figure 4 shows the yield strength of mild steel vs temperature. As can be seen, heating the preform dramatically reduces the forces required to consolidate the particulate mixture into a cermet. Two standard industrial processes to consolidate the preform and particulate mixture currently exist.

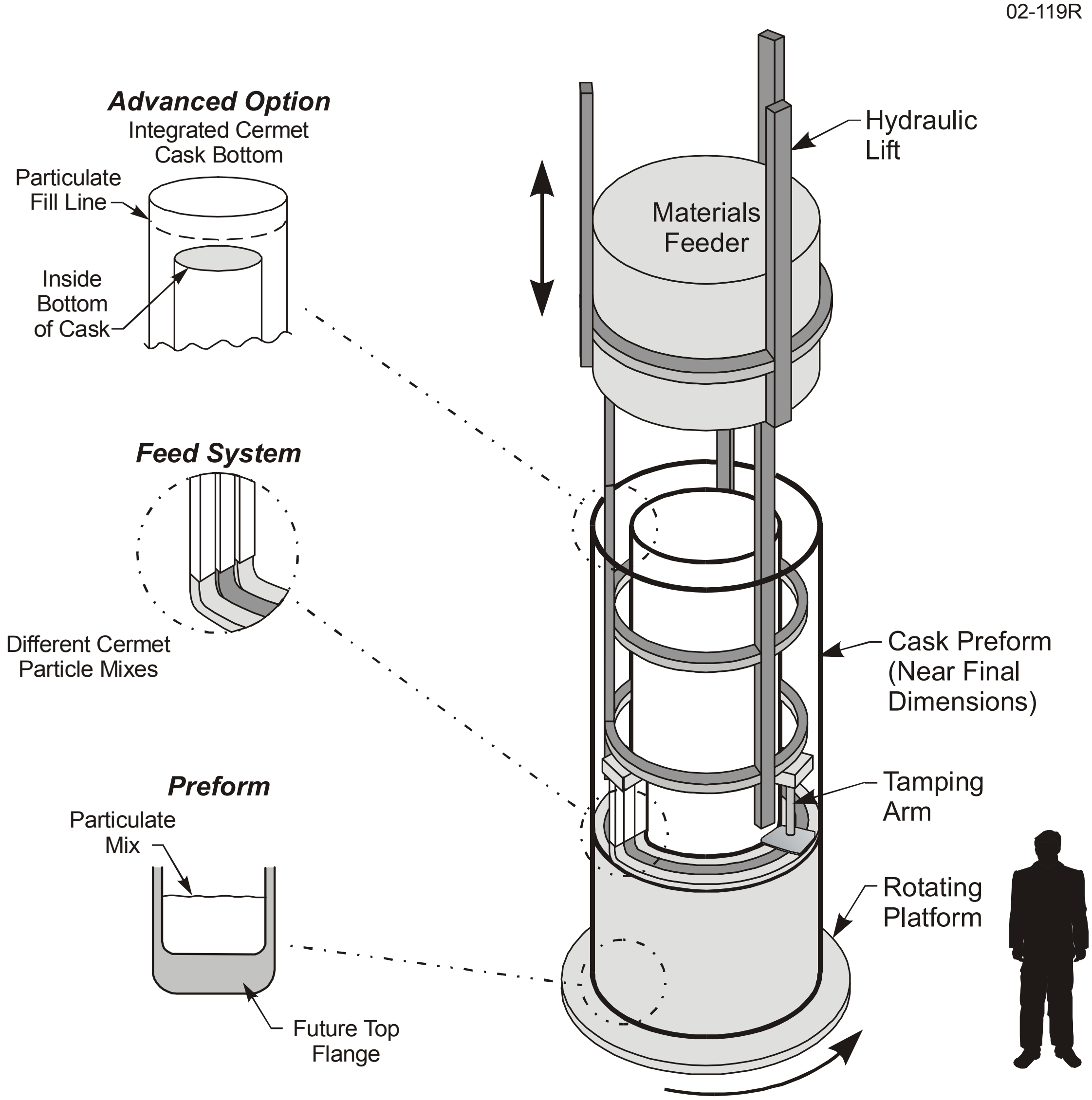

Fig. 3. Loading cermet preform with variable particulate compositions DUO_2, other ceramics, and steel powder.

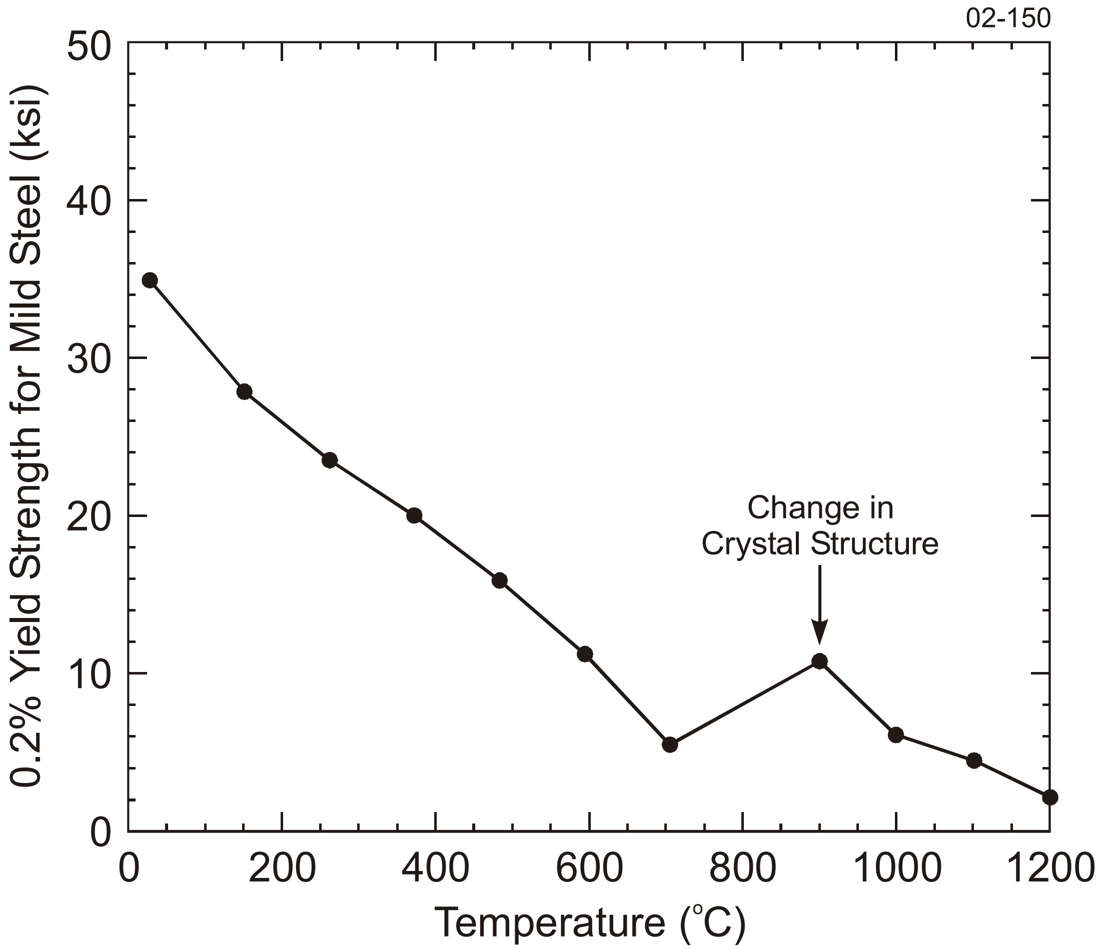

Fig. 4. Yield strength of mild steel vs temperature.

- <u>Traditional forging.</u> The hot, heated perform can be hammered to consolidate the particulate mixture into a cermet and produce the final cask form. In one method shown in Fig. 2, a cylindrical anvil, the size of the interior of the final cask, is placed inside the preform. The forge then strikes the exterior to consolidate the particulate mixture. While the cask may weigh 100 tons, forges in the United States can form parts up to 500 tons in weight.

- <u>Ring-rolling forging.</u> The hot loaded preform can be placed in a ring-rolling machine and rolled to its final form (Fig. 2).

- *Finishing*. The cask bottom is welded onto the cylindrical cask body. After completion of this step, a vertical boring mill is used to obtain the final dimensions and to drill holes in the top of the cask for the lid bolts. While the steel preform thickness in the center of the cask may be 1 to 2 cm, the preform thickness near the lid may be 10 to 20 cm to allow for bolt holes and attachment of other hardware.

Many fabrication variants exist. The preform can include the bottom of the cask (Fig. 3). Note that the cask body is upside down during the fill operation. Although this technique allows a preform that incorporates the cask bottom, more-sophisticated forging operations are required to produce the final cermet.

This cask fabrication process has several defining characteristics. The fabrication technique allows the use of variable cermet composition within the cask body to optimize properties. No cermet welding is required and because the cask body from the forging process is very close to the final dimensions, machining is minimized.

In terms of manufacturing, this powder metallurgical method limits the handling of radioactive DUO_2 to the filling of the preform, a room-temperature operation that requires limited space and limited capital investment and generates little radioactive wastes. All of the remaining operations involve handling and processing of a sealed container with DUO_2. Such a process restricts the health physics operations required for handling the DUO_2 to a very small area and may allow the use of commercial shops for the forging and machining steps. This, in turn, limits the front-end investment—a major concern with a new enterprise.

Powder metallurgy production techniques have the potential for low costs. Millions of tons of iron and steel powders are produced for the fabrication of many products; thus, the costs of raw materials are low. The current cost for steel powder purchased in large quantities is about $600/ton.

IV. COMPARISONS

The powder metallurgy approach provides greater freedom in the design of the cermet cask by allowing variable cermet properties in three dimensions and permitting cermets to be fabricated using materials that are normally considered to be incompatible. Casting methods require that molten metal "wet" the DUO_2 or other particulates (SiC, etc.) to avoid the formation of void spaces caused by trapped gases between particulates, thus making it necessary to add selected alloying agents to the metal to improve wetability. Centrifugal casting of multiple-layer (clean steel, DUO_2 cermet, etc.) casks requires that the outer layer have the highest melting point and that the inner layer have the lowest melting point. Gravitational effects in casting operations result in settling of the denser DUO_2 in the molten steel, which constrains the volume ratio of ceramic to metal for any given ceramic particle size distribution.

Casting methods require a greater volume of equipment to be in contact with the DUO_2, thus generating significant wastes. However, because the operations of an electric furnace with DUO_2 particulates and clean steel or DUO_2 particulates and potentially contaminated steel are identical, the casking options allow the easy reuse of suspect contaminated recycle metal, with potential cost savings in materials and avoidance of disposal costs. If recycle of potentially contaminated steel is desired using the powder metallurgy route, an electric furnace and several other pieces of process equipment are required to produce the metal powder.

Because of the front-end capital investment, the economics of casting are strongly dependent upon the throughput. Centrifugal casting machines for objects the size of SNF casks are 15 m in height, with the top of the casting machine below the floor level of the steel mill. Two electric furnaces are required: one for clean metal and one for the DUO_2 particulates dispersed in molten steel. After the facility is set up, incremental production costs for each additional cask are low. The powder metallurgy route has the potential for low costs at low throughput—if the sealed preform can be processed at existing industrial forging facilities.

Ongoing studies will better define the capabilities and costs for these alternative fabrication technologies. Preferred fabrication methods will depend upon (1) the cermet cask requirements—powder metallurgical techniques give greater freedom to the cask designer, (2) success in developing the different methods for fabricating a DUO_2–steel cermet cask, and (3) expected scale of operations. Significant research and development is required for any of the potentially viable fabrication technologies.

ACKNOWLEDGMENTS

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