Cask Size and Weight Reduction Through the Use of Depleted Uranium Dioxide (DUO_2)–Steel Cermet Material

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ABSTRACT

Newly developed depleted uranium (DU) composite materials enable fabrication of spent nuclear fuel (SNF) transport and storage casks that are smaller and lighter in weight than casks made with conventional materials. One such material is DU dioxide (DUO_2)–steel cermet. This work examines the radiation shielding efficiency of this new cermet material as compared with conventional steel used in Holtec International's HI-STAR 100 cask system. In this analysis, the steel layers of the HI-STAR 100 cask are replaced with a layer of cermet material. The thickness of the cermet shielding is adjusted to give the same radiation doses as the HI-STAR 100 cask. When gamma radiation dose alone is considered, the best-case outside radius (70% DUO_2 in steel) is reduced from 121 to 113 cm and the weight is reduced from 77 to 61 tons. When 1% B_4C neutron absorber is added to the nominal case (49% DUO_2 in steel), the cask outside radius is reduced from 121 to 108 cm and the cask weight is reduced from 77 to 72 tons. The radial cross-section shielding area is reduced 41%. These calculations assume a constant 85-cm radius for the multipurpose canister that contains 24 pressurized-water-reactor fuel assemblies. These reduced sizes and weights will significantly influence the design of next-generation SNF casks.

INTRODUCTION

Newly developed depleted uranium (DU) composite materials enable fabrication of spent nuclear fuel (SNF) transport and storage casks that are smaller and lighter in weight than casks made with conventional materials. This work examines the possible use of DU-steel cermet as a shielding material in SNF storage casks. The DU, in the form of the dioxide (DUO_2), is mixed with a continuous phase of steel, creating a DU-steel cermet material. A schematic of DUO_2-steel cermet is shown in Figure 1. There are numerous benefits in using cermet as the shielding material in storage casks. Because of the more efficient shielding of the cermet, the cask is smaller in size, making it more likely to fit through restrictive doorways. As a result of its smaller size, the cask is also lighter in weight, enabling the use of lower-capacity hoists during handling operations. A cermet cask will also have a higher thermal conductivity than concrete shielded casks, allowing for higher decay heat content. Because DU cermets are already used for armor on battle tanks in the U.S. Army (1), it is believed that the cermet will be more resistant to terrorist assault.

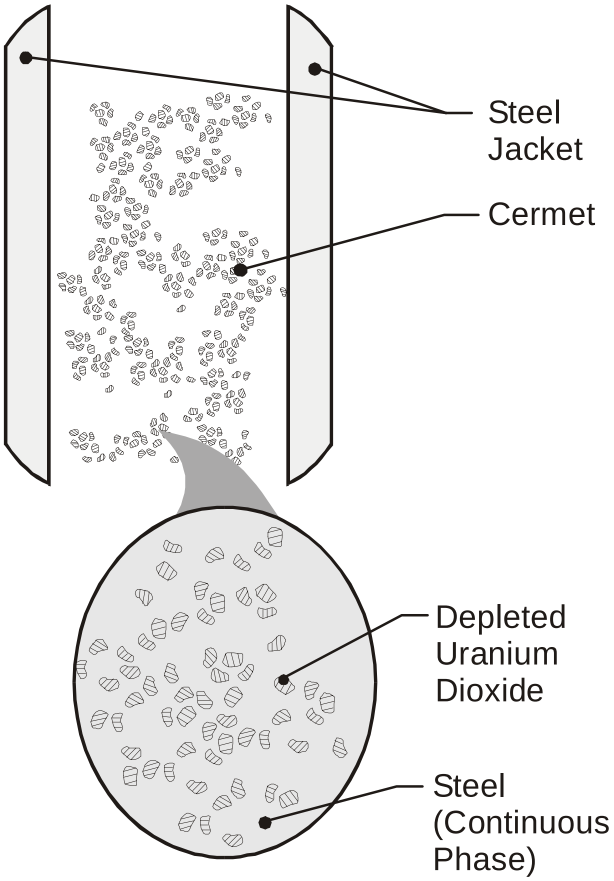

Figure 1 Basic concept of DUO_2-steel cermet

The cermet SNF cask is based upon the Holtec International Corporation (Holtec) HI-STAR 100 storage and transport cask system. Holtec has a cooperative research and development agreement with Oak Ridge National Laboratory (ORNL) to develop cermet materials for the next-generation transport and storage cask system.

Radiation source calculations are based on the Holtec Multi-Purpose Canister-24 (MPC-24), an SNF canister for 24 pressurized-water-reactor (PWR) fuel assemblies. Figure 2 shows a schematic of the HI-STAR cask and the inner MPC-24 structure. The HI-STAR cask has two primary layers of shielding. The inner layer consists of SA 516 and SA 203 steel for gamma shielding and structural strength (2). The outer layer is Holtite-A, a neutron-shielding hydrogenous material developed and licensed by Holtec. This work calculated the radiation dose at the outside surface of the cask when the inner steel gamma shield is replaced with a DU-steel cermet layer. The inner dimensions of the HI-STAR cask remain unchanged to allow for the continued use of the Holtec MPC-24.

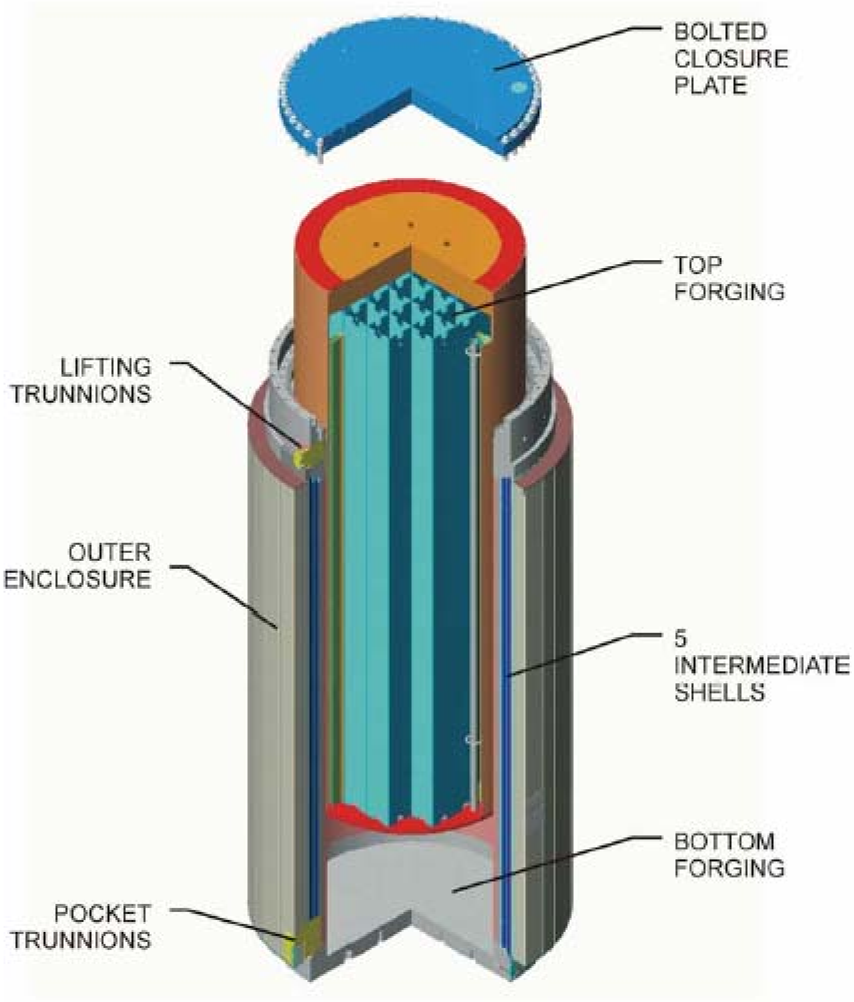

Figure 2 Basic layout of Holtec's HI-STAR rail transport and storage cask

DU is produced as a by-product of uranium enrichment. The current U.S. Department of Energy inventory of DU is ~500,000 MT (1) and is increasing at a rate of ~20,000 MT/year. The cost to safely dispose of this large amount of DU has been estimated to be $241 million–$1.5 billion, depending on the method of disposal. Rather than incurring the cost of disposing of the DU, a beneficial use is sought (e.g., the use of DUO_2 as shielding material in SNF transport and storage casks).

ASSUMPTIONS AND METHODOLOGY

Radiation shielding thicknesses for different materials were calculated for the same gamma and neutron dose at the outer cask surface. The MPC-24 was the same for all cases. After modeling the HI-STAR 100 cask, the steel shielding layers of this cask were replaced with layers of different cermet materials. The thickness of the cermet shielding was adjusted to give the same surface radiation dose as the HI-STAR cask.

The source radiation term for these shielding calculations was obtained from an output file of the ORIGEN-ARP program in the SCALE 4.4a code system. The SCALE code system is available from the Radiation Safety Information Computational Center at ORNL. The input data for ORIGEN-ARP were generated from data obtained in the Final Safety Analysis Report (FSAR) for the Holtec HI-STAR 100 (2). All calculations performed for this project assumed that the storage cask contained the Babcock and Wilcox (B&W) PWR fuel in a Holtec MPC-24 (see Table I).

Table I Input data for ORIGEN-ARP Express for B&W 15 × 15 PWR spent fuel

Parameter	Input
Fuel type	15 × 15
Uranium	1.18916E+07 g
Enrichment	3.4%
Burnup	40,000 MWd/MTU
Cycles	3
Libraries	1
Cooling time	5 years
Power history	≥ 90%
Average power	40 MW/MTU

The SAS1 module from the SCALE 4.4a package (3) was used for all shielding calculations. The SAS1 module of SCALE uses standard SCALE composition libraries and the functional modules BONAMI-S, NITAWL-S, XSDRNPM-S, and XSDOSE to perform one-dimensional shielding calculations. The radiation calculations used 27 energy groups of neutrons and 18 energy groups of gamma. Standard energy group boundaries from the SCALE code were used in ORIGEN-ARP and SAS1 module calculations.

RESULTS AND ANALYSIS

The calculation results for the reference-case modeled HI-STAR cask are listed in Table II, and the results for the cermet casks are presented in Tables III and IV. Table III lists the outer radii of the modeled cermet casks and the percentage loss to the original outer diameter. The weight estimates for the cermet casks compared with those for the HI-STAR cask are shown in Table IV. As indicated in Table IV, the thickness of the steel liner can affect the cask weight by up to 2.5 tons depending on the volume percent of DUO_2 in the cermet. The volume percent of DUO_2 in the cermet has a greater effect on the weight of the cask, causing variations of as much as 3.1 tons in the case of the smallest 30% DUO_2 and the smallest 50% DUO_2. The change in diameter of the cask is not as pronounced as the change in cask weight, because the inner radius, which cannot be changed, represents ~75% of the cask diameter. However, the weight of shielding material required for sufficient gamma shielding is reduced by ~20%. Although the percentage changes do not appear to be large, they offer significant advantages. The possibility of fitting more SNF assemblies in a cask that has a weight similar to that of the current HI-STAR cask will reduce costs, which are largely related to the number of fuel assemblies handled.

The possibility of adding an embedded neutron absorber into the cermet material was briefly examined. Calculations show that to obtain the same total dose, gamma and neutrons, from a cermet cask with 1% B_4C embedded, requires only 18 cm (7.09 in.) of the cermet material. The B_4C cermet cask has a diameter that is 10% smaller than that of the HI-STAR 100 cask. The cross-sectional area of shielding on the cermet with B_4C is only 49.7% that of the HI-STAR 100 casks. The neutron-shielding capability of the B_4C cermet cask can be further improved by reducing the percent of ^{235}U present in the DU. Table V shows the neutron doses received when various percentages of ^{235}U are present in the DU. The difference between a cask with 0.4% ^{235}U in the DUO_2 and a cask with only 0.1% ^{235}U is a reduction of 10% in the neutron dose on the cask surface.

Table II HI-STAR parameters

Weight listed in the FSAR	Modeled shielding weight	Modeled outer radius
77 tons	61.54 tons	120.81 cm

Table III Sizes for modeled cermet casks

Inner steel shell thickness cm (in.)	Outer steel shell thickness cm (in.)	Thickness of cermet required cm (in.)	Total steel and cermet thickness cm (in.)	Outer Radius cm (in.)	% Outer radius
30% by volume DUO_2 cermet cask					
0.635 (0.25)	0.635 (0.25)	15.8 (6.220)	17.07 (6.720)	116.29 (58.14)	96.26
0.635 (0.25)	1.27 (0.5)	15.3 (6.024)	17.205 (6.774)	116.42 (58.21)	96.37
1.27 (0.5)	1.27 (0.5)	14.8 (5.827)	17.34 (6.827)	116.56 (58.28)	96.48
1.27 (0.5)	2.54 (1)	13.8 (5.433)	17.61 (6.933)	117.83 (58.91)	97.53
50% by volume DUO_2 cermet cask					
0.635 (0.25)	0.635 (0.25)	14 (5.512)	15.27 (6.012)	114.49 (57.24)	94.77
0.635 (0.25)	1.27 (0.5)	13.6 (5.354)	15.505 (6.104)	114.72 (57.36)	94.96
Nominal					
1.27 (0.5)	**1.27 (0.5)**	**13.2 (5.197)**	**15.74 (6.197)**	**114.96 (57.48)**	**95.16**
1.27 (0.5)	2.54 (1)	12.3 (4.843)	16.11 (6.343)	115.33 (57.66)	95.46
70% by volume DUO_2 cermet cask					
Best Case					
0.635 (0.25)	**0.635 (0.25)**	**12.7 (5.000)**	**13.97 (5.500)**	**113.19 (56.59)**	**93.69**
0.635 (0.25)	1.27 (0.5)	12.3 (4.843)	14.205 (5.593)	113.42 (56.71)	93.89
1.27 (0.5)	1.27 (0.5)	11.9 (4.685)	14.44 (5.685)	113.66 (56.83)	94.08
1.27 (0.5)	2.54 (1)	11.1 (4.370)	14.91 (5.870)	114.13 (57.06)	94.47

Table IV Weight reduction for cermet casks

Inner steel shell thickness		Outer steel shell thickness		Thickness of cermet required		Conservative cask weight (tons)	Nominal cask weight (tons)	Nominal percent weight	Nonconservative cask weight (tons)
cm	**(in.)**	**cm**	**(in.)**	**cm**	**(in.)**				
30% by volume DUO_2 cermet cask									
0.635	(0.25)	0.635	(0.25)	15.8	(6.220)	67.59	66.87	89.16	66.29
0.635	(0.25)	1.27	(0.5)	15.3	(6.024)	67.79	67.08	89.44	66.51
1.27	(0.5)	1.27	(0.5)	14.8	(5.827)	68.02	67.33	89.78	66.78
1.27	(0.5)	2.54	(1)	13.8	(5.433)	68.43	67.77	90.36	67.24
50% by volume DUO_2 cermet cask									
0.635	(0.25)	0.635	(0.25)	14	(5.512)	64.67	63.73	84.98	62.98
0.635	(0.25)	1.27	(0.5)	13.6	(5.354)	65.10	64.19	85.59	63.47
Nominal									
1.27	**(0.5)**	**1.27**	**(0.5)**	**13.2**	**(5.197)**	**65.57**	**64.70**	**86.27**	**64.01**
1.27	(0.5)	2.54	(1)	12.3	(4.843)	66.10	65.27	87.02	64.60
70% by volume DUO_2 cermet cask									
Best Case									
0.635	**(0.25)**	**0.635**	**(0.25)**	**12.7**	**(5.000)**	**62.84**	**61.77**	**82.37**	**60.9**
0.635	(0.25)	1.27	(0.5)	12.3	(4.843)	63.18	62.14	82.85	61.30
1.27	(0.5)	1.27	(0.5)	11.9	(4.685)	63.58	62.56	83.42	61.75
1.27	(0.5)	2.54	(1)	11.1	(4.370)	64.26	63.30	84.40	62.53

Weight does not include fuel or multipurpose canister.

Table V Effect of ^{235}U in B_4C cermet on surface neutron dose

Percent ^{235}U in the DUO_2 used to make the cermet	**Neutron dose on cask surface (mrem)**	**Percent reduction from 0.4%**
0.4	75.70	-
0.3	73.17	3.4
0.2	70.62	6.7
0.1	68.06	10.1
0.05	66.77	11.8

CONCLUSIONS

The most likely configuration for a cermet cask is one in which the volume percent of DUO_2 is 50% in the cermet and the steel liners are 1.27 cm thick. With this configuration, the outside radius of the cask decreases from 120.81 to 114.96 cm and the weight is reduced from 77 to 64.7 t. This decrease equals a weight reduction of 12.9 to 16% of the HI-STAR 100 weight. With cermet material composed of 70% by volume DUO_2, the diameter of the cask can be as small as 113.19 cm. The weight of a best-case cask is 17.6% lower than that of the HI-STAR weighing 61.8 tons. For SNF casks these improvements are more significant than they may at first seem. The significance of any reduction in the weight of a cask is magnified during loading operations. Lower cask weight means lower crane-handling capacities, which make operations easier and safer. Reductions of cask diameter of up to 6.3% mean loaded casks are more likely to fit through restricting passageways. However, the most promising aspect of the cermet material lies in future studies utilizing a neutron absorber within the cermet material. This process reduces the cask size by another ~4.5% and reduces the complexity of cask manufacturing. When an embedded neutron absorber is used, the cask radiation dose becomes dominated by the neutron dose. These calculations assumed the use of a 0.3% ^{235}U content in the DUO_2. If this percentage of ^{235}U is lowered, the neutron dose will decrease because less fissioning of the ^{235}U occurs in the cermet. Another promising application of the cermet material is in truck transport casks. Currently, only a few PWR assemblies fit into a truck transport cask. However, with the reduced weight and size of shielding required with the cermet material, more fuel assemblies can be transported per cask via truck. The characteristics of possible cermet casks and the HI-STAR cask are summarized in Table VI.

The results of this work are summarized in Figure 3.

Table VI Summary of conclusions

	Weight (tons)	**Percent weight reduction**	**Radius (cm)**	**Percent radius reduction**
Nominal (50% UO_2) cermet cask	64.7	13.7	114.96	4.8
Best (75% UO_2) cermet cask	61.8	17.6	113.19	6.3
Cermet (49% UO_2) cask with 1% embedded B_4C neutron absorber	67.43*	10.1	107.75*	10.8

*Neutron dose dominates this configuration. Using DU less than the 0.3% ^{235}U assumed will lower the dose and therefore the weight and dimensions.

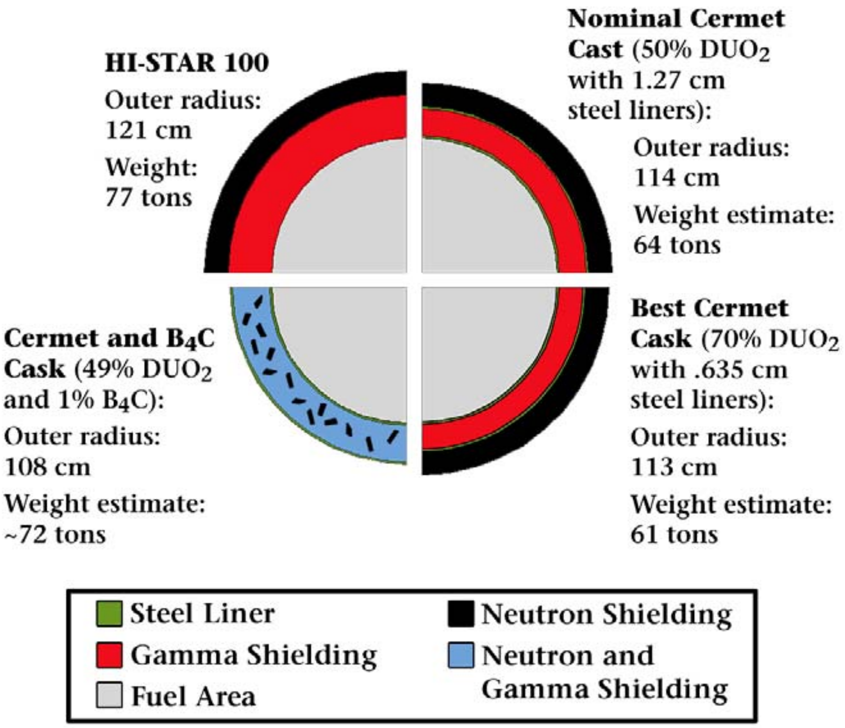

Figure 3 Cask size and weight reduction through the use of DUO$_2$-steel cermet material

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