Analyses of U.S. and R. F. Depleted-Uranium Concrete/Steel Transport and Storage Cask for Spent Nuclear Fuel

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Abstract – The depleted uranium (DU) inventory in the U.S. exceeds 500,000 metric tons (tonnes). A large portion of the U.S. inventory of DU can be used in the fabrication of nuclear shielding for the storage, transport, and disposal of spent nuclear fuels (SNF). Oak Ridge National Laboratory (ORNL) researchers analyzed the production of this shielding material based on work done at the Idaho National Laboratory (INL), measured the DUO_2–aggregates' physical properties and chemical durability, estimated capital and production costs of SNF casks using DU concrete (DUCRETE™), and studied the shielding properties of this material when used for SNF cask manufacturing.

The All-Russian Scientific-Research Institute of Experimental Physics (VNIINM) Russian researchers have also developed DUCRETE to fabricate spent fuel casks. Essentially, the VNIINM process has modified the production of concrete aggregate and as a result of these studies has proposed a simpler process for spent fuel cask manufacturing.

This paper describes (a) the process derived from the INL studies, (b) the results of the shielding analysis, (c) the concrete aggregate process developed at the VNIINM, and (d) economic analysis of incorporating the Russian modifications into the process and fabrication technologies previously analyzed by ORNL.

Results show reduced cask weight and size when using the DUCRETE material to replace the conventional concrete. The cost analysis performed in this study also indicated a reduction in SNF cask overall production cost of ~10% by adding the process modifications suggested by researchers of VNIINM.

I. BACKGROUND

I.A. DUCRETE Origins and Development in the United States

One of the uses for the large U.S. inventory of depleted uranium (DU)—which exceeds 500,000 metric tons (tonnes)—is nuclear shielding. A research program being conducted by the U.S. Department of Energy (DOE) envisions that a large portion of this DU will be used in the fabrication of nuclear shielding casks for the storage, transport, and disposal of spent nuclear fuel (SNF). DU metal has been used in special casks as shielding because its high density provides the needed gamma attenuation for the lowest-weight and smallest casks. Studies have assessed the use of uranium metal for shielding in both spent fuel and high-level waste casks.[1,2] A review of DU metal production and fabrication costs showed that DU metal was much more expensive than other common shielding materials such as steel, lead, and concrete.[3] Therefore, the primary projected application for uranium metal shielding is for transportation casks, where the most stringent total-package size and weight limits exist and where high-cost DU metal shielding can be justified. Projected uses of DU oxides for shielding are primarily for SNF storage casks.

DU concrete (DUCRETE™) and DU aggregate (DUAGG™) technologies enable an expanded role in multipurpose casks. There is an additional benefit to the nuclear community because this use as shielding will consume a large quantity of surplus DU from the existing national inventory.

DUCRETE consists of a DU ceramic (DUAGG) that replaces the coarse aggregate used in standard concrete. This DUO_2 ceramic is a very dense, stable, low-cost coarse aggregate that is combined with Portland cement, sand, and water in the same volumetric ratios used for ordinary concrete. If the ceramic can be produced at a low enough cost, it would be practical to consider using DUCRETE concrete as a shielding material.[4] The cost of concrete cask fabrication is low when compared with fabricating steel, lead, and DU metal casks. Emulating nuclear fuel fabrication technology, researchers sintered uranium oxide (UO_x) into aggregate with very high density. Using DUAGG and DUCRETE with density exceeding 6.7 g/cm^3 (398.7 lb/ft^3) can be manufactured.

I.A.1. Radiation Shielding Analysis Performed at Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL)

Preliminary analysis done for cask manufacturing indicated that the DU composite materials enable fabrication of SNF transport and storage casks that are smaller and lighter in weight than casks made with conventional materials.[5] Further analysis done by ORNL examined the radiation shielding efficiency of DUCRETE as compared with a conventional concrete cask that holds 32 pressurized-water reactor (PWR) SNF assemblies.[6] In this analysis, conventional concrete shielding material is replaced with DUCRETE. The thickness of the DUCRETE shielding is adjusted to give the same radiation surface dose, 200 mrem/h, as the conventional concrete cask. It was found that the concrete shielding thickness decreased from 71 to 20 cm; the cask radial cross-section shielding area is reduced ~50%. The weight was reduced ~21% from 155 tons to ~126 tons. Should one choose to add an extra outer ring of SNF assemblies, the number of SNF would increase from 32 to 52. In this case, the outside cask diameter would still decrease, from 169 cm to137 cm. But, the weight would increase somewhat from 155 to 177 t. Gamma radiation (not neutron) is the dominate contributor to total cask surface dose. Neutron cask surface dose is only ~10% of the gamma dose. These reduced sizes and weights will significantly influence the design of next-generation SNF casks.

Spent fuel distribution is illustrated in Fig. 1 for conventional concrete storage cask and DUCRETE cask. The geometric distribution of spent fuel considered for this study is also shown in Fig. 1 where the black squares represent available positions for spent fuel assemblies. In this geometric configuration, the use of DUCRETE casks increases the number of SNF assemblies being contained from 32 to 52. Future studies will consider different geometric distributions. Figure 1(a) shows the cross-section for the reference conventional concrete storage cask for PWR fuel. It contains neutron flux traps. If the U.S. Nuclear Regulatory Commission (NRC) allows burn-up credit for PWR fuel, then the cask represented by cross section shown in Fig. 1(b) becomes applicable. Most electric utilities who own PWRs are buying casks such as that shown in Fig. 1(b) in anticipation of NRC approval of burn-up credit for PWR fuel during storage. Figure 1(c) is the cask shown in 1(b) when DUCRETE replaces the conventional concrete. Note the large reduction in shielding thickness from 71 to 20 cm. Similarly, weight is reduced from 155 to 126 tons. There is no difference among inner stainless steel liner radii in cases 1(a), 1(b), and 1(c). In case 1(d), an additional ring of SNF is added to the reference case [Fig. 1(b)] and the cavity radius increases from 87.9 to 103 cm. Even when an extra ring of SNF assembles is added, the outside radius of the cask is reduced from 169 to 137 cm. However, the total weight of the cask increases from 155 to 177 tons.

I.A.2. Conceptual DUCRETE Models Analyzed by Sierra Nuclear

Sierra Nuclear developed a conceptual model of its VSC-24 storage casks with DUCRETE. This dry-storage cask is capable of storing 24 PWR or 61 boiling-water-reactor fuel assemblies. Through a series of calculations, Sierra Nuclear showed that such a storage cask is about ~15% lighter than one made of ordinary concrete and has a much smaller footprint on the storage pad. The Sierra Nuclear DUCRETE storage cask has a diameter of 90 in. (228 cm), compared with 132 in. (335 cm) for standard heavy concretes casks which use magnetite (iron oxide) or barite (barium sulfate) for their dense aggregates.

I.A.3. Production Process Development: Formation of DUAGG

Research has been performed by INL and ORNL to define a production process first, for DUAGG (the aggregate that constitutes the DUCRETE) and second, DUCRETE (the main component for SNF cask manufacturing). The proposed process of conversion of the stockpiled UF_6, for which a production plant is now under construction at Paducah and Portsmouth, produces DU_3O_8 that can be reduced to DUO_2 powder or fine granules. DUO_2 is the basic material used in the formation of DUAGG, which is the concrete aggregate used to make the DUCRETE for the SNF casks. Direct use of this fine DU oxide has two limitations. First, concretes depend on their coarse aggregates to carry compressive stresses. If the shielding is required to have significant compressive strength (>4500 psi), the powder must be sintered into dense aggregate pellets with sufficient strength to be used in high-strength concretes. If the shielding is not required to provide compressive strength, as in some cask designs, this untreated DUO_2 powder still cannot be used to form even a low-strength, fine grout because of its chemical reactivity. The second limitation is that in an oxygenated environment (aerobic conditions), very dense DUO_2 inevitably oxidizes to form less dense UO_3 and even lighter U_3O_8, resulting in destabilizing expansions of the concrete/grout matrices. Therefore, the raw DUO_2 must be treated and formed for use in stable high-strength concretes.

Quapp and Lessing resolved these two issues by using a basaltic sintering agent that both reduced the pellets' sintering temperatures and made a protective coating of the DUO_2 that chemically stabilized the DUAGG in cement paste matrices.[7,8] Therefore, they made it possible to make very stable, high-strength concretes with over three times the density of standard construction concretes.

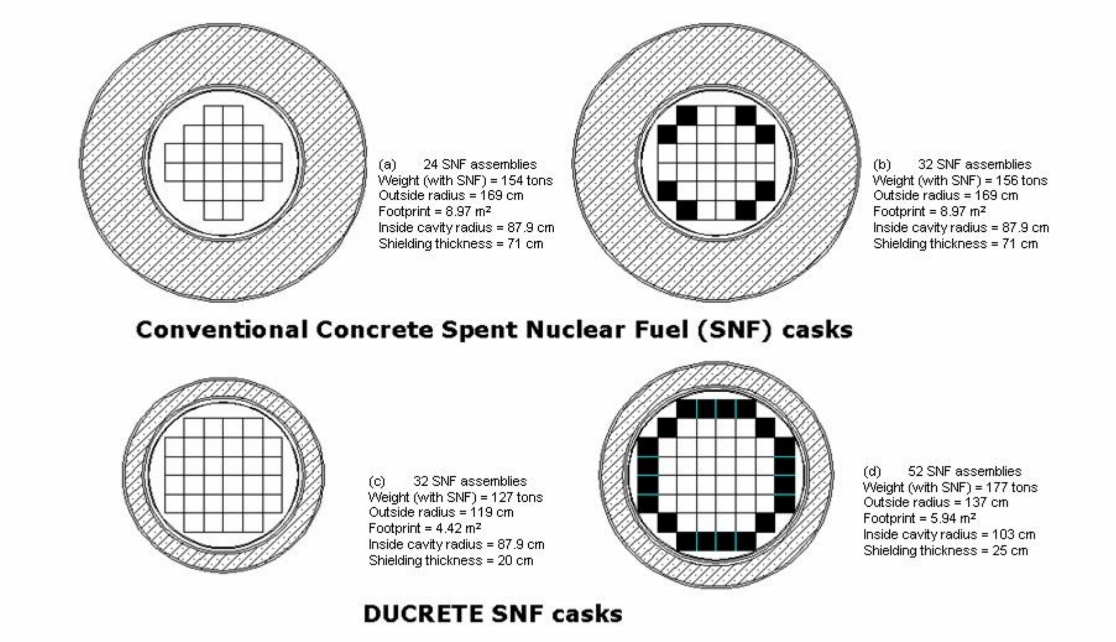

Fig.1. Cask Size and Weight Reduction Through the Use of DUCRETE.

I.B. Work in Russia on DUCRETE Optimization

Work has been done in collaboration with Russian scientists at the All-Russian Scientific-Research Institute of Experimental Physics (VNIINM) to analyze the use of DUCRETE for cask manufacturing and to confront the dilemma of producing a competitive process for the cask production.[9] The issues analyzed in this work were related to a number of contradictory requirements on the application of high-density concrete as structural and radiation shielding material in casks for SNF storage. On the one hand, the DUCRETE manufacturing components should not be expensive and commercially available, on the other hand, the material should provide high strength and density (that increases the absorption of ionizing radiation), tolerable thermal conductivities, radiation and corrosion resistance, long service life, and water resistance.

The DU particles must be preliminarily coarsened (aggregated) and the UO_2 chemical resistance must be improved through additives to introduce UO_2 into the concrete composition. The specific characteristics of UO_2's chemical activity because of its small size of particles and thus great specific surface area prevent the use of traditional methods of UO_2 introduction into concrete composition.

The INL binder consisted of glass, titanium oxide, zirconium titanate, and zirconium oxide. The VNIINM binder included also zirconium silicate. UO_2 ceramics produced at VNIINM showed that the increase of compacting pressure up to a certain value results in an increase of density after sintering. However, further increase of compacting pressure causes density reduction in the final product. The optimum value of compacting pressure was then determined for the specified blend. These tests showed that there was a reduction of density caused by increasing the initial heat rate during the sintering process.

The process that VNIINM suggested after its laboratory tests consists of the following steps:

- mixing components,
- pressing with green pellets,
- crushing green pellets to obtain the required size fraction and distributions,
- drying, and
- sintering of green pellets to form a graded final product with further cooling.

The VNIINM process changes offer advantages in the production technology. It does not require crushing and sizing. Eliminating the crushing procedure allows reducing energy consumption and avoiding dust containing UO_2. Figures 2 and 3 illustrate the production technologies of ceramics using the original U.S. STARMET process and modified VNIINM process, respectively.

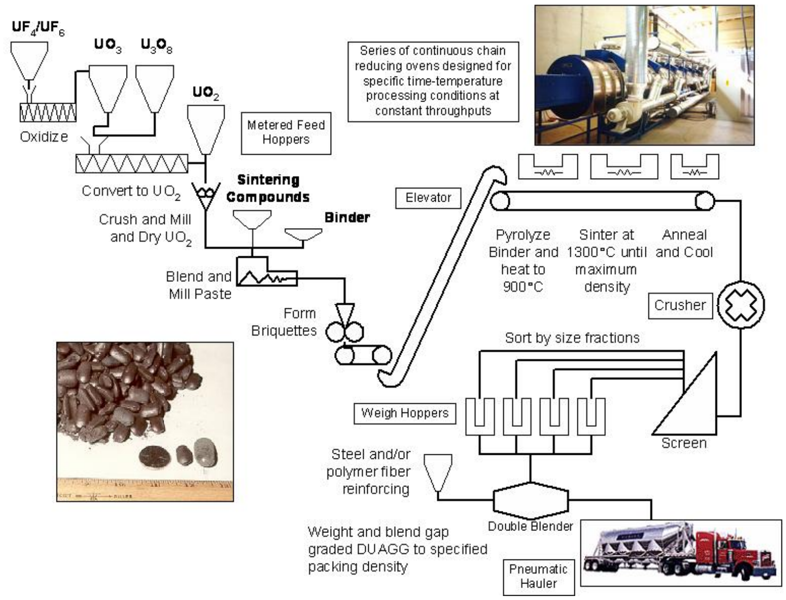

Fig. 2. Ceramics production using the U.S. technology.

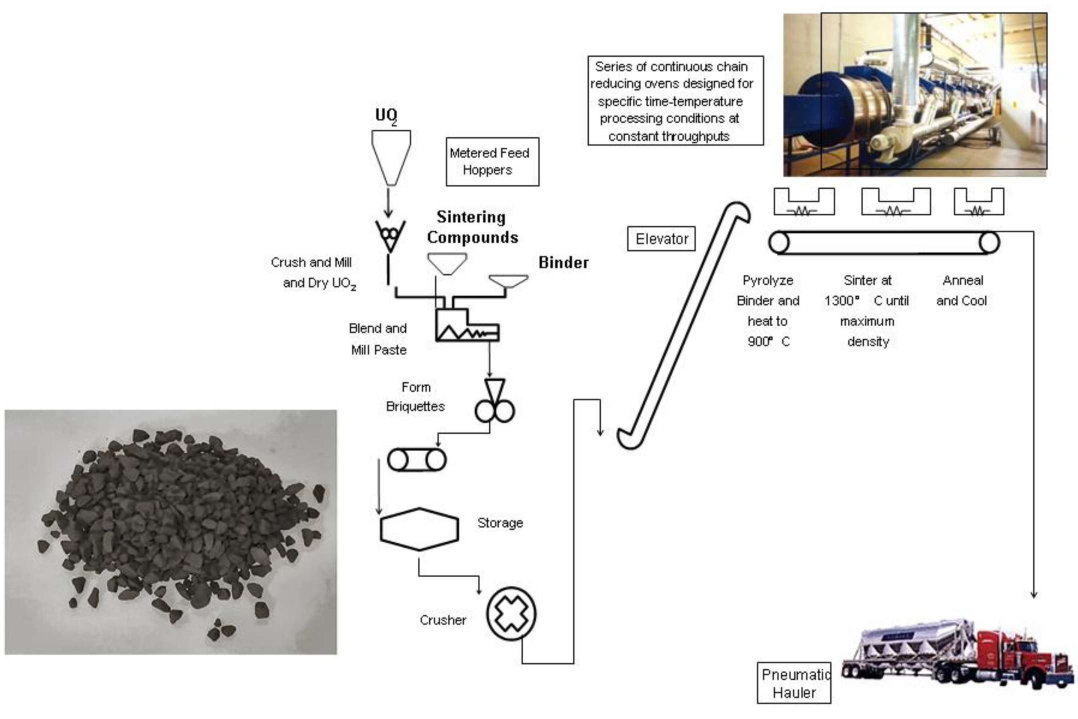

Fig. 3. Ceramics production using the VNIINM technology.

II. PROCESS REVISION BASED ON VNIINM WORK

II.A. Preconceptual Plant Design and Cost Studies of DUAGG Production

The purpose of this analysis is to establish the viability of the DUAGG production process as a private commercial venture, incorporating the Russian experimental data. To ascertain the commercial viability of the project, the modified baseline DUAGG production plant equipment layout for a preconceptual dry process production plant is shown in Fig. 4. The production rate is assumed to support an SNF market penetration of 30% in the domestic demand for casks. This would require sufficient DUAGG production to make 50 SNF casks per year, which requires 2834 tonnes of DUO_2 to form 3114 tonnes of DUAGG.

Previous economic studies have indicated that the total capital cost for the baseline DUAGG plant is ~$11.6M. Most of the equipment can be readily obtained off-the-shelf from national vendors.[10,11]

Table 1 indicates the total capital cost estimate, assuming that the original baseline plant has been modified based on the studies done in Russia. The total estimated capital cost is ~$8.4M. Most of the equipment can be readily obtained off-the-shelf from national and international vendors. Reduction in costs was possible because the engineering cost for this plant is lower; there is less equipment, less building expenses, and other smaller additional investments. Operation costs for the modified baseline are described in Table 2. A capital cost recovery factor of 25% was included in the production cost. There are two analyzed variables in this cost estimate. First, the production cost assumes that it is possible to obtain a credit for using DUO_2 of $384/ton of DUO_2 for projected disposal costs (DOE saves money for not disposing of DUO_2 as a waste) and second, the U.S. domestic labor cost varied between $40 and $80/h.

The operating cost for the baseline of the modified production plant was $5.4M ($108K/cask) for a labor cost of $80/h and $4M ($80K/cask) for a labor of $40/h. Previous analysis for the baseline DUAGG production plant indicated that the total operating cost for the baseline process was ~$6.4M ($129K/cask) for a labor cost of $80/h and $4.7M ($94.9K/cask) for a labor cost of $40/h. As reference for the baseline production plant and including the credit for the beneficial use of DUO_2, the total operating cost was estimated as $5.2M ($104K/cask) for a labor cost of $80/h and $3.8M ($76K/cask) for a labor cost of $40/h. In all cases, cost savings are realized by using the production process used in the VNIINM plant design.

II.B. DUCRETE/Steel Cask Production Costs

The complete cask manufacturing cycle includes the preparation of the DUCRETE and the cask manufacturing process (Fig. 5). A baseline flowsheet was developed with the unit operations involved in cask manufacturing. The economic analysis estimates the production cost of SNF casks made with DUCRETE.

The economic analysis focuses on (1) the design of a SNF cask plant that receives DUAGG for the production of DUCRETE, (2) the DUAGG that will be used in high-strength DUCRETE for SNF casks, and (3) potential cost elements that can vary when the project is in place. The process receives DUAGG from an external source that most likely will be the new DUF_6 conversion-to-oxide plant. The final product consists of SNF casks that are transportable and can be used for storage. In the future, a potential exists for the cask to be used for disposal purposes at the repository.

The cask facility will receive prefabricated inner and outer cylinders, lids, and covers for the casks. It is assumed that 3 days would be necessary (one shift per day) to completely produce one cask. The plant will work 5 days/week or 150 days/year (30 weeks/year or 1200 h/year).

This production rate establishes the size of the equipment needed to implement the production schedule as well as the site support facilities and the plant layout. The capital and operating costs were determined based on the unit-operations equipment used as shown in the flowsheet, the layout of the plant, and the labor requirements.

Table 3 summarizes the operating cost for the baseline case.

Based on the total yearly operating cost of ~$23,750,000, the manufacturing cost per cask would be $455,000. This table does not include licensing, marketing, transportation, or other significant costs. The ultimate goal is to sell storage casks for about half a million dollars. This result shows that DUCRETE casks can be manufactured and sold at a cost that could be competitive in today’s market.

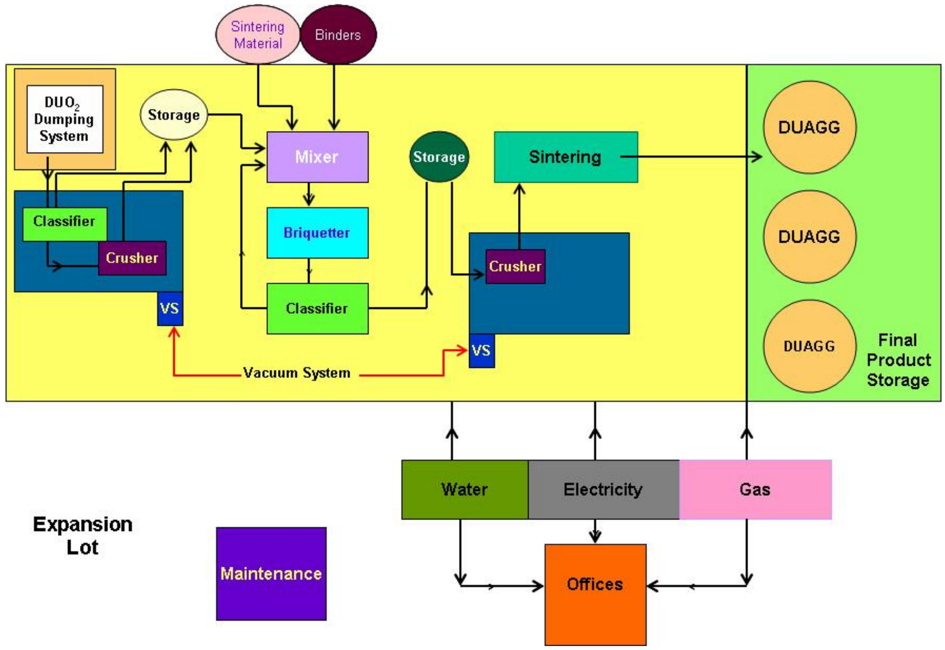

Fig. 4. Layout of the process equipment to produce VNIINM DUAGG.

Table 1. Estimated capital cost for the VNIINM baseline case

Capital cost item	Cost estimate including modifications derived from Russian studies ($) (2004 dollar value)
Civil/site preparation	500,000
Utilities building services	56,000
Process equipment, land, and buildings	3,854,000
Special process services	35,000
Engineering	618,000
Piping	192,000
Installation labor	482,000
Electrical	97,000
Spare parts	78,000
Management	482,000
Shipping	96,350
Safety system	231,240
Contingencies	1,680,398
Total capital cost	8,401,988

Table 2. **Production cost for DUAGG incorporating modifications to the baseline**

	$384/tonne DUO_2 credit		Baseline: zero-cost DUO_2	
	Labor cost ($/h)		Labor cost ($/h)	
	80	**40**	**80**	**40**
Capital	$8.4M	$8.4M	$8.4M	$8.4M
Operating (year)	$4.3M	$2.9M	$5.4M	$4M
Unit (cask)	$86K ($1.5/kg)	$58K ($1.02/kg)	$108K ($1.89/kg)	$80K ($1.40/kg)

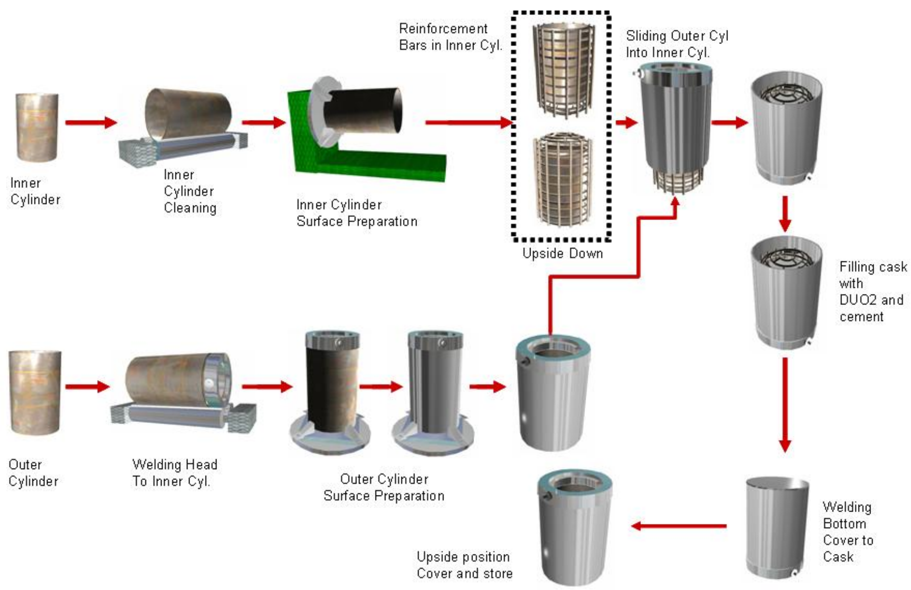

Fig. 5. Flowsheet showing the use of DUCRETE in cask manufacturing.

Table 3. Baseline case estimates for the operating cost of DUCRETE cask manufacturing

Cost item	Cost estimate ($/year)
Labor	11,337,000
Steel (inner and outer cylinders, covers, lids, reinforcement @$33,000/cask)	1,675,000
DUAGG (assumed the most conservative cost of the material @$108,000/cask)	5,400,000
Cement	100,000
Waste management	500,000
Energy	100,000
Capital recovery (assumed 4 years of recovery or 25%)	4,620,000
Total operating cost, $/year	**23,732,000**

III. ANALYSIS AND CONCLUSIONS

- DUAGG cannot be produced in the United States at a cost that is competitive with conventional barium sulfate aggregate. The cost of DUAGG is ~$1000–$2000/tonne, whereas delivered graded barium aggregate is ~$340/tonne. The cost for DUAGG in an advanced SNF cask is ~$58,000–$108,000, which leaves a margin for the completion of the production process that should result in a total cost per cask that meets the goal of ~$550,000.

- The commercial viability of DUAGG/DUCRETE depends on its potential to enable improved, unique cask performance characteristics. For example:

  – DUCRETE may permit smaller, lighter-weight casks that can be transported by railcar,

  – DUCRETE may permit casks to contain more spent fuel assemblies at lower maximum temperatures within current volume and weight limits, and

  – DUCRETE may also enable the removal of the extensive matrix of rebar in current concrete cask designs.

- Operating costs dominate unit costs. Labor cost (~60%) is the largest contributor to baseline operating costs. Furthermore, the production at VNIINM or offshore can significantly reduce the costs. Capital cost recovery is ~25% of annual operating costs.

- Unit operating costs are sensitive to the credit, if any, of UO_2 feed materials. A credit of $384/tonne reduces the unit cost between 20 and 27%. This credit is assumed for the cost avoidance of disposing of DU_3O_8.

- Operating costs (security, health physics, licensing) could be greatly reduced if the DUAGG fabrication plant were colocated with another uranium processing facility such as the UF_6 conversion plant.

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