# BENEFICIAL USES OF DEPLETED URANIUM

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## INTRODUCTION

Naturally occurring uranium contains 0.71 wt % $^{235}U$. In order for the uranium to be useful in most fission reactors, it must be enriched—the concentration of the fissile isotope $^{235}U$ must be increased. Depleted uranium (DU) is a co-product of the processing of natural uranium to produce enriched uranium, and DU has a $^{235}U$ concentration of <0.71 wt %. In the United States, essentially all of the DU inventory is in the chemical form of uranium hexafluoride ($UF_6$) and is stored in large cylinders above ground. If this co-product material were to be declared surplus, converted to a stable oxide form, and disposed, the costs are estimated to be several billion dollars.

Only small amounts of DU have at this time been beneficially reused. The U.S. Department of Energy (DOE) has begun the Beneficial Uses of DU Project to identify large-scale uses of DU and encourage its reuse for the primary purpose of potentially reducing the cost and expediting the disposition of the DU inventory. This paper discusses the inventory of DU and its rate of increase; DU disposition options; beneficial use options; a preliminary cost analysis; and major technical, institutional, and regulatory issues to be resolved.

## INVENTORY OF DU

Major uranium enrichment facilities, and therefore substantial DU inventories, exist in the United States, Russia, and France. The locations of inventories in the United States are given in



[2]Managed by Lockheed Martin Energy Research Corp., under contract DE-AC05-96OR22464 for the U.S. Department of Energy.

Table 1, and estimated worldwide inventories are given in Table 2 (ref. 1). The content of $^{235}U$ in DU is dependent on economics. If the cost of natural uranium feed is high relative to the cost of enrichment services, then a low $^{235}U$ content in the DU, such as 0.2 wt %, is chosen. Conversely, if natural uranium feed is relatively inexpensive, the $^{235}U$ content in the DU may be around 0.3 wt %. In the United States, about 60% of the DU have enrichments <0.3 wt % (ref. 1).

Approximately 560,000 million grams uranium (MgU) [560,000 metric tons (t)] of depleted $UF_6$ [i.e., 407,000 MgU (≈407,000 t) as uranium] were stored on DOE sites as of July 1, 1993, when DOE still managed uranium enrichment operations. Since the U.S. Enrichment Corporation (USEC) took over these operations, it has produced additional DU for which it is responsible. The USEC inventory of DU is increasing at a rate of ~20,000 Mg/year (~20,000 t/year). Depleted $UF_6$ is stored as a solid in 10- to 14-ton steel cylinders, most of which are ~3.66 m (~12 ft) long and ~1.22 m (4 ft) in diam. There are ~47,000 cylinders in storage; 29,000 are at Paducah, 13,000 at Portsmouth, and 5,000 at the site of the former Oak Ridge Gaseous Diffusion Plant (now called the East Tennessee Technology Park). The cylinders are generally stored outdoors, stacked two high, resting on concrete or wooden storage chocks on gravel, asphalt, or concrete storage yards.[2]

## DISPOSITION OPTIONS

DOE initiated a program in 1994 to reconsider its approach to the long-term management of the DU in storage. In November 1994, DOE requested recommendations for alternative management strategies and uses for DU from a variety of organizations and from the general public. Fifty-seven responses were received, representing a total of 70 recommendations.[2] These responses provide the basis for the management alternatives developed for study in the Draft Programmatic Environmental Impact Statement (PEIS) now nearing completion.[3] The alternatives being considered in the PEIS are: (1) no-action, (2) long-term storage as depleted $UF_6$, (3) long-term storage as an oxide of uranium, (4) use of DU as an oxide or as a metal, and (5) disposal of depleted $UF_6$ as an oxide. This paper discusses the “use” alterative.

The conversion of $UF_6$ to a chemically stable oxide, such as uranium dioxide ($UO_2$) or triuranium octaoxide ($U_3O_8$), also produces a fluorine compound [typically anhydrous hydrogen fluoride (HF) or hydrofluoric acid] as a co-product. One potential option for reuse of the fluorine is to produce more $UF_6$ feed material for gaseous diffusion plants, and there are many other uses of fluorine. Such uses are not discussed herein, but the value of the co-product fluorine may be used to partially offset the cost of converting the $UF_6$ to a more usable form.

## Table 1. Quantities of DU by material form and site, MgU[a] (t)

| Material form | Paducah | Portsmouth | Oak Ridge | Savannah River | Fernald | Argonne | Rocky Flats | Other sites | Total | Percentage of total |
|---|---|---|---|---|---|---|---|---|---|---|
| $UF_6$ | 230,000 | 110,000 | 37,000 | | | | | | 377,000 | 92.7 |
| $UF_4$ | 1,260 | | | | 1,950 | | | | 3,210 | 0.8 |
| Oxide | | | | 19,430 | 40 | | | | 19,470 | 4.8 |
| Metal-unalloyed | | | 1,450 | 1,700 | 1,870 | | | 480 | 5,500 | 1.4 |
| Metal-alloyed | | | 180 | 900 | | 180 | 120 | 200 | 1,580 | 0.4 |
| Total | 231,260 | 110,000 | 38,630 | 22,030 | 3,860 | 180 | 120 | 680 | 406,760 | 100.0 |
| Percentage of total | 56.9 | 27.0 | 9.5 | 5.4 | 0.9 | 0.0 | 0.0 | 0.2 | 100.0 | |

[a]MgU = millions of grams uranium.

**Table 2. World-wide inventories of DU**

| Enricher | Estimated 12/31/95 inventory, MgU (t) | Estimated annual increase MgU/year (t/year) | Storage form |
|---|---|---|---|
| United States | 470,000 | 20,000 | $UF_6$ |
| France (Eurodif) | 135,000 | 12,000 | $U_3O_8$ |
| Urenco[a] | 29,000 | 4,000 | $UF_6$ |
| United Kingdom (BNFL) | 30,000 | 0 | $UF_6$ |
| Russia | 430,000[b] | 10,000[b] | $UF_6$ |
| Japan | 2,600 | 500 | $UF_6$ |
| South Africa | 2,200 | 0 | $UF_6$ |
| China | 20,000[b] | 1,000[b] | unknown |
| Others | <1,000 | unknown | unknown |

[a]Urenco operates plants in Germany, the Netherlands, and the United Kingdom.
[b]Estimated.

Source: Ingemar Lindhol, "Depleted Uranium: Valuable Energy Source or Waste for Disposal?" paper given at the 21st Annual Symposium of the Uranium Institute.

## BENEFICIAL USES

Some historical beneficial uses for DU are as follows:

- *Further enrichment.* DOE originally undertook the long-term storage of DU because it could be used in the future as feed for further enrichment. The low cost of uranium ore and postponed deployment of advanced enrichment technology have indefinitely delayed this application.

- *Nuclear reactor fuel.* DU can be used as a fertile material to create plutonium in fast breeder reactors. This plutonium can then be blended with more DU to make mixed oxide (MOX) fuel (typically about 6% Pu and 94% DU) for thermal reactors. Implementation of a civilian advanced reactor fuel cycle, including breeder reactors, and the accompanying recycle of nuclear fuel, would require a significant change in national policy. However, use of DU is being planned as a part of the military plutonium disposition option in which it will be transformed into MOX fuel for existing reactors.

- *Down-blending high-enriched uranium (HEU).* Nuclear disarmament negotiations may lead to the down-blending of some weapons-grade HEU with DU to make commercial reactor fuel.

- *Munitions.* This use of DU metal is in conventional military applications such as tank armor and armor-piercing projectiles. This demand is decreasing as environmental regulations become more complex.

- *Biological shielding.* DU metal has a high density, which makes it suitable for shielding from x-rays or gamma rays for radiation protection.

- *Counterweights.* Because of its high density, DU has been used to make small but heavy counterweights for such applications as the aircraft industry.

One characteristic of all these applications is that their DU consumption rate is low; therefore, they do not have a significant effect on the huge inventory of DU for the foreseeable future. DOE would prefer (a) to see the entire DU inventory cost-effectively consumed in beneficial uses and (b) to avoid the direct disposal of this material. Figure 1 shows some of the beneficial uses of DU, the amount of the DU inventory they may consume, and a subjective judgement of the developmental status of each.

## POTENTIAL HIGH–CONSUMPTION USES

During the last few years, a number of novel beneficial uses of DU have been identified. Some of these have the potential for consuming a significant portion of the DU inventory. Three important new beneficial uses of DU are to (1) make a high-density concrete to use in manufacturing containers for radioactive material storage; (2) place DU oxide near spent nuclear fuel waste packages at the high-level waste (HLW) repository to reduce the possibility of nuclear criticality, provide shielding from radiation, and improve post-closure chemical isolation; and (3) clad DU metal counterweights for forklift trucks.

### HIGH-DENSITY DU SHIELDING

A large potential market for DU is in radiation shielding applications. DU metal has been used in such applications, but its relatively high cost has justified such use only when its high density can justify the premium. However, if depleted $UF_6$ were converted to a more stable chemical form of uranium (e.g., oxide, carbide), it could be used as a component of the primary shielding material in containers designed to store and, in some cases, dispose of spent nuclear fuel, low-level or high-level radioactive wastes. The high density of uranium compounds makes them excellent components as shields from photon radiation.

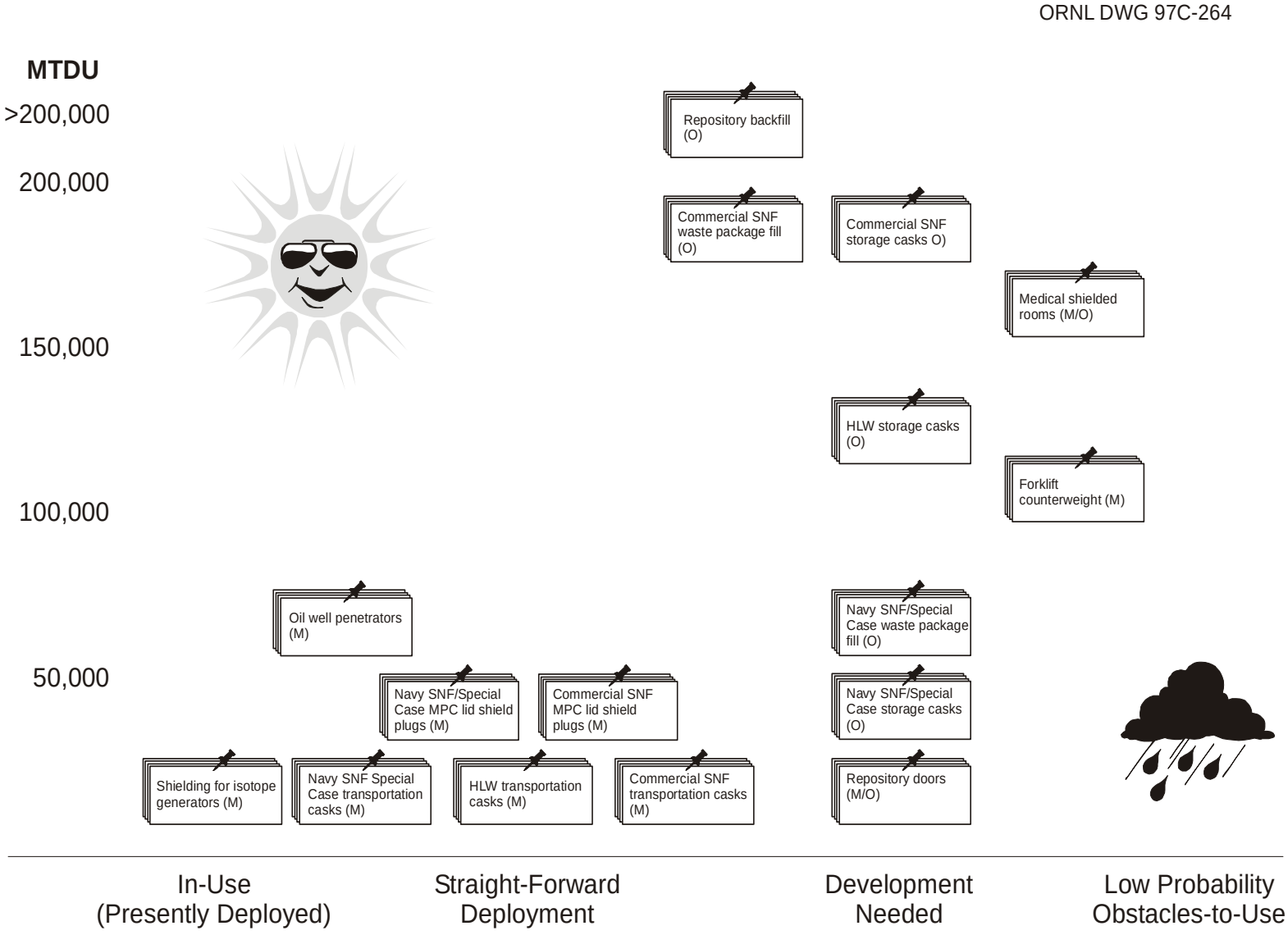


**Fig. 1. Beneficial uses of DU.**

One attractive DU shielding concept involves making a "heavy" concrete using a DU compound as one of the components of the concrete. If a DU compound is used to make the concrete, the same shielding performance could be achieved with up to half the thickness required of normal concrete, depending on the form of the DU. In this approach, the uranium compound is substituted for the course aggregate in conventional concrete and is enclosed between annular stainless steel shells that make up the body of the container to provide predictable structural strength.

The most advanced DU concrete technology involves converting the DU to uranium dioxide particles, aggregating the particles into briquettes using a special binder, and sintering the briquettes to form a dense aggregate called DUAGG.[4] The DUAGG is combined with conventional concrete-forming materials (e.g., cement, sand, and water) to form an ultra-high density concrete named DUCRETE™. This concrete weighs 6,407 kg/m$^3$ (>400 lb/ft$^3$), compared to ~2,114 kg/m$^3$ (~132 lb/ft$^3$) for conventional concrete.[5] DUCRETE™ has been patented in the United States for DOE by Lockheed Martin Idaho Technologies, the operations contractor at Idaho National Engineering and Environmental Laboratory (INEEL). Nuclear Metals, Inc., (NMI) of Concord, Massachusetts, has entered into an exclusive world-wide license agreement to commercialize the DUCRETE™ process. NMI is currently installing pilot-scale equipment at its wholly owned subsidiary, Carolina Metals, Inc., of Barnwell, South Carolina.

A project has been proposed to DOE-EM to process 9,000 Mg (9,000 t) of stored depleted $UO_3$ from the Savannah River Site into at least 2,000 DUCRETE™ self-shielded storage boxes for radioactive wastes at Fernald and additional shielded containers for INEEL.

DUCRETE™ has also been proposed for use in constructing dry spent fuel storage shields for on-site storage of civilian reactor fuel. In this application the use of DUCRETE™ results in smaller shield size and lower weight. Conceptual design studies[6] have shown that a ventilated storage container for dry spent nuclear fuel storage similar to the Sierra Nuclear Corporation VSC-24 can be made from such high density concrete. Although the fuel load (24 spent pressurized-water reactor fuel assemblies) is the same as a container made of conventional concrete, the external diameter is reduced by about 1 m (40 in.)—from about 3.3 m (130 in.) to 2.3 m (90 in). The total weight is reduced from about 135 Mg (135 t) to about 100 Mg (100 t). This is predicted to significantly reduce the cost of storage container loading by eliminating the need for transfer casks while simultaneously reducing occupational radiation dose.

Other technologies have been proposed for making high-density DU shielding, although they are less advanced than DUCRETE™. One technology would involve converting the DU to the carbide, coating these with carbon using technology similar to that developed to manufacture High-Temperature Gas-Cooled Reactor fuel, and then using the resulting particles to make a DU concrete. Another proposal is to use polyethylene as a binder for DU aggregate to form the high-density shielding. The various technologies for making high-density DU shielding have not been comparatively evaluated.

The use of DU aggregate in high-density shielding has the potential of consuming the entire DU inventory. However, there are technical issues associated with this option. For DUCRETE™, issues needing further study include optimum DU aggregate formulations (e.g., preferred uranium oxide state—$UO_2$, $U_3O_8$, or $UO_3$) and optimum aggregate size(s). Various binder materials need to be investigated. Additional information is needed concerning the thermo-mechanical-chemical performance of heavy concrete. For example, the thermal conductivity, mechanical strength, and long-term stability under elevated temperatures and oxidizing conditions must be determined. More information is also needed on the fabricability of heavy concrete, with issues such as pourability and homogeneity (i.e., settling of aggregate and/or filling of interstices). The development status of the other technologies is less clear, but similar issues would seem to be relevant: the preferred form of the aggregate, binder, and the mixture thereof; the properties, stability, and performance of the product; and manufacturing techniques for large items.

## DU OXIDE USED AS CASK FILL MATERIAL, REPOSITORY INVERT MATERIAL, OR BACKFILL MATERIAL

Oak Ridge National Laboratory (ORNL) scientists have proposed a new spent fuel package fill technology in which DU dioxide is placed in the voids of spent nuclear fuel waste containers for storage, transport, or disposal[7]. This concept is intended to provide shielding, reduce the potential for repository nuclear criticality events, and reduce the long-term release of radionuclides from spent nuclear fuel at the repository. In this concept, empty waste packages would be loaded with spent nuclear fuel. The void space between the fuel pins and outer void between spent fuel assemblies and the inner waste package wall, which would ordinarily be filled with helium gas, would instead be filled with small depleted $UO_2$ particles. The repository waste package would then be sealed. The use of fill material (not uranium oxides) has been extensively investigated for Canadian waste packages. The thin-walled, particulate-packed containers were selected as the design for the reference engineering study for the Concept Assessment Phase of the Canadian Nuclear Fuel Waste Management Program.[8]

The presence of the highly dense $UO_2$ would reduce the external shielding requirements and radiation dose to repository materials. The depleted $UO_2$ should reduce the probability of short-term and long-term nuclear criticality incidents by lowering the average enrichment inside the waste package to well below 1 wt % $^{235}U$ equivalent. Finally, the $UO_2$ fill has the potential to reduce the long-term release of radioactive constituents of the spent fuel into the environment. Most of these radionuclides are incorporated into the $UO_2$ pellets of the spent nuclear fuel, and would not be released unless the waste package fails and the spent nuclear fuel $UO_2$ crystal structure were to be destroyed. The depleted $UO_2$ fill material would react with groundwater before the water reaches the fuel material and suppresses the dissolution of the spent nuclear fuel if the outer barriers of the waste package failed. Suppression of dissolution is projected to occur via multiple chemical mechanisms: maintenance of chemically reducing conditions within the waste package, saturation of the groundwater in the degraded waste package with uranium, and reduction of degraded waste package permeability to air and water flow. The use of DU as fill material in spent nuclear fuel packages is estimated to consume approximately one-half of the entire DU inventory.

Some of these improvements are possible when DU oxide particulates are used as a component of invert and backfill material at the repository. Waste repository "invert" is material placed in the bottom of the tunnel to form a flat foundation for operating equipment and waste packages. Once all waste packages are placed in the repository and it is decided that in situ monitoring and human activities can cease, the repository tunnels would be loaded with material termed "backfill," which will be crushed native rock under current plans. Some of the potential advantages of using DU oxides as fill material in waste packages listed above may apply to the use of DU oxides as a component of repository invert and backfill materials, although (a) they may be less effective when the DU oxide is further away from the spent nuclear fuel and (b) it is clear that neither could offer shielding or internal criticality control advantages, and that invert could not beneficially affect the groundwater stream entering a failed waste package.

Development work needs revolve around three sets of technical issues: (1) material characteristics and insertion: optimal particle sizes and shape, chemical form, binder/diluent for backfill and invert, insertion techniques for fill and backfill; (2) performance improvement: determining the nature, extent, and probability of potential benefits to improving crush resistance, and ameliorating shielding, criticality, and radionuclide dissolution and transport issues; and (3) performance degradation: determining the nature, extent, and probability of potential adverse impacts such as increased temperatures or damage caused by insertion of fill or backfill. Substantial design work must be done to demonstrate that the process of filling the waste package with depleted $UO_2$ particulates does not damage the spent nuclear fuel and is practical from a dust generation and control perspective. Similarly, experimental verification of the thermal behavior of the waste package with fill material is required.

These concepts are relatively new, so no commercial development has taken place.

## COUNTERWEIGHTS FOR FORKLIFT TRUCKS

There are beneficial nonnuclear uses of DU because of its physical and chemical properties. Yet, there are substantial institutional and regulatory hurdles to overcome before it can be used by companies that do not have a radioactive material license. There are also issues associated with the public acceptance of widespread use of a radioactive material such as uranium. Counterweights for forklifts are being considered as candidates for a prototype demonstration for general public uses of DU.

Design engineers have attempted to reduce the physical size of forklifts to gain greater maneuverability in more confined spaces since the first production models of forklifts were introduced in the 1920s. For this reason, forklift manufacturers have designed and redesigned iron counterweights to maximize the lifting capacity ratings while minimizing the turning radius to accommodate narrow aisles in warehouses and plants. Forklift design has been optimized, and dramatic further improvements are unlikely using iron as a counterweight.

It has been stated by forklift industry leaders that the mere substitution of uranium metal for iron counter weights will revolutionize the industry by ushering in design concepts not previously available. DU metal counterbalances, clad in protective steel shielding, can significantly reduce the physical size of the present standard iron counterweight. Iron metal weighs 7,000 $Mg/m^3$ (~437 $lb/ft^3$), while uranium metal weighs ~19,000 $kg/m^3$ (~1,186 $lb/ft^3$). A typical 2.27 Mg (5,000-lb) capacity forklift requires 1.33 Mg (2,922 lb), or 0.19 $m^3$ (6.69 $ft^3$), of iron counterweight and adds about 0.58 m (23 in.) of length to the rear of the machine. Conversely, the same 2.27 Mg (5,000-lb) capacity forklift utilizing DU metal for the counterweight can achieve the needed ballast with 0.07 $m^3$ (2.46 $ft^3$) of metal and only 11.43 cm (4.5 in.) added on the rear. When this reduction in overall length is applied to the crucial right-angle stacking (the amount of space required to execute a 90° turn) dimension of the forklift, the result is a 10% increase in usable warehouse floor space. Therefore, the DU metal counterweight will provide a 10% per square foot cost savings when computing the building costs of a new warehouse.[9] If DU metal counterweights were used exclusively in the United States forklift industry, the DU inventory would be consumed in 3.7 years.[9] This concept is being developed by T. Roberts and Associates of Paducah, Kentucky.

Technical issues requiring further evaluation include the demonstration of the ability to cask large quantities of molten uranium metal in steel molds. Feasibility tests have been successful on a small scale. A competitive cost of uranium metal fabrication needs to be established. The use of uranium metal counterweights will enable innovative forklift designs, which would require a prototype demonstration. Institutional and regulatory issues may be more daunting. The control of each uranium metal casting must be exhibited, because the location of each casting must be known at all times. The technology must be available to the general public without a radioactive material license. Finally, the public must accept uranium use in general commercial applications.

## COST ANALYSIS

There are two major economic driving forces for the beneficial use of DU. First, DU management represents a potential financial and safety liability to DOE. The DU is currently stored in aging metal cylinders, and if the $UF_6$ is contacted with water as a result of cylinder corrosion or accidents, toxic hydrofluoric acid vapors would result. Cylinders are regularly inspected, and corrective maintenance activities such as restacking cylinders, lining, or replacing wooden storage chocks, and replacing or refurbishing cylinders are performed as needed. An estimated $10 million is spent each year to store $UF_6$ and maintain containers in the United States.[10] Beneficial use of this material would probably lead to an earlier disposition than simply continuing storage, which would reduce this cost more quickly.

Also, as noted in the introduction, nonbeneficial disposition would probably involve a sequence of conversion of the DU to a stable oxide with sale of the fluorine-bearing co-products, if possible; transportation of the DU oxide to a disposal site; and subsequent burial. The costs of this disposition are at least several billion dollars and could be over $10 billion if worst-case

disposal requirements were imposed.[11] The rationale for pursuing beneficial uses of DU is that, in the best of worlds, the use of DU will be cost effective in its own right and save a major portion of the nonbeneficial disposition cost. However, if this is not the case, then an acceptable outcome is that the system-wide life-cycle cost of beneficial use of DU to meet various needs would be less than the cost of nonbeneficial disposition of the DU plus the cost of employing conventional technologies to meet the same needs. Because the cost of converting DU hexafluoride to the oxide would be incurred in both conventional (in preparation for long-term storage or disposal) and beneficial use (to make DU concrete, fill materials, etc.) scenarios, the cost difference between them is essentially the potential long-term storage or disposal cost of the DU.

Unfortunately, the uncertainties in the technologies (and thus the costs, of beneficially using DU) are large relative to the cost difference between beneficial and nonbeneficial DU use scenarios. This is the case because:

- Most DU beneficial uses are still at an early stage of development, and their costs are not well known. In some cases, fundamental information related to feasibility is not yet in hand.

- The cost of disposing of DU spans a wide range because of uncertainties in the nature of the disposal site and waste acceptance criteria.

- Some of the uses (e.g., DU fill) have benefits for which there is no conventional counterpart.

- Some significant benefits depend on subtleties in existing limits and approaches that can be identified only with detailed cost analyses by experts. One example of this is the potential to eliminate spent fuel transfer casks if DU concrete storage casks are used, the feasibility of which is heavily dependent on not exceeding site-specific threshold weight limits.

- The need to consider system-wide, life-cycle costs which requires mounting a major effort with careful attention to detail and closure.

While the PEIS should offer additional insights into the costs, it is likely that a sufficiently accurate cost assessment must await additional experimental data and the more definitive designs that will result therefrom. The following paragraphs provide a qualitative insight into some of the preliminary cost studies performed to date.

DU heavy concrete can be used as shielding in the spent nuclear fuel HLW casks at a cost estimated to be comparable to the lower of the DU direct disposal cost estimates.[5] Consequently, the case can be made that DU heavy concrete-shielded casks are an economic, viable alternative to direct DU disposal. A beneficial system-wide long-term solution to DU management is attained for much less than the combined cost of independently providing shielded casks and disposing of the DU. The DU concrete casks must be disposed of once they are no longer

needed, if they cannot be used as part of the waste package container during ultimate disposal. The location of this cask disposal, perhaps at a near-surface repository or a geologic repository, has not yet been established.

Current spent nuclear fuel dry storage applications almost exclusively use concrete. It seems logical that DU heavy concrete could be substituted in this application. Capital costs for DU concrete ventilated storage casks are comparable to current spent nuclear fuel concrete cask costs.[6] This analysis assumes no cost for the DU oxide, and excludes licensing, design, engineering, project management costs, etc. An additional ~10% is required for higher construction costs and stainless steel inner and outer shells. Note also that capital concrete cask costs are approximately doubled to transform DU into acceptable aggregate form.

Costs for using DU as fill material in geologic repository waste packages and as invert and backfill material at the repository have not been evaluated.

While the cost difference between beneficial and nonbeneficial DU disposition scenarios is essentially independent of the DU hexafluoride conversion cost, the absolute cost of either scenario is heavily dependent on this process step. The cost of conversion is 50–75% of the total cost of scenarios other than those involving a high disposal cost. More cost-effective conversion technologies are being investigated in an effort to reduce this cost. Additionally, the potential for beneficial use of the fluorine-bearing co-products is being investigated, although the association of this co-product with a radioactive material may be an impediment. Converting $UF_6$ to metal is generally significantly more costly than conversion to the oxide, and improved technologies are also being considered in this area.

## CONCLUSIONS

The DU in the DOE complex is an asset with realistic potential for system-wide, cost-effective uses, and multiple such beneficial uses are being actively pursued for this material. Private industry has been enthusiastic about finding beneficial uses for the large DU inventory. DOE is working closely with industry to develop mutually beneficial arrangements for use of the DU.

Major outstanding issues include addressing a number of technical aspects of the potential beneficial uses of DU, obtaining regulatory and user acceptance of the beneficial uses, and appropriately allocating the costs and benefits of beneficial DU use.

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