COST-EFFECTIVENESS OF UTILIZING SURPLUS DEPLETED URANIUM (DU)

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ABSTRACT

About a billion pounds of surplus depleted uranium (DU) has been produced as a by-product of the uranium enrichment process for defense programs and civilian nuclear reactors at the gaseous diffusion plants at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. A project is under way to convert this DU hexafluoride (DUF_6) into a more stable oxide form that is predominately DU_3O_8. Baseline plans are to dispose of the conversion plant product in radioactive waste disposal facilities in Nevada or Utah. Finding a beneficial use for this material, rather than disposing of it, could save the U.S. government hundreds of millions, if not billions, of dollars.

This work reports estimated order-of-magnitude costs for DU_3O_8 packaging; transportation from Paducah, Kentucky; and disposal at the Nevada Test Site (NTS). Disposal charges were assumed to be $9/ft^3, based on discussions with NTS staff. The results cover a range of values, because the number of containers that results depends on the bulk density of the material that is produced and can range from 1.5 to 4.0 MT/m^3. The limiting criterion is 40,000 lb/truck load shipment, per U.S. Department of Transportation rules. The weight of a single container is assumed to be 0.53 MT, the amount contained in a 55-gal drum. The cost avoidance to the U.S. Department of Energy is estimated as follows:

Table I

Packaging	$93B170M
Transportation	$88B160M
Disposal	$60B100M
Total	$241B430M

Some beneficial commercial uses of DU and their potential markets are described. The revenues from sales of casks constructed of DUO_2 composite materials are estimated to be as much as $0.5B/year.

INTRODUCTION

Naturally occurring uranium contains 0.71 wt % ^{235}U. In order for uranium to be useful in most nuclear applications, the concentration of the fissile isotope ^{235}U must be increased by a process called enrichment. The enrichment of uranium creates a by-product, depleted uranium (DU), in which the concentration of ^{235}U is <0.71 wt %. The U.S. government has ~500,000 MT of DU stored at U.S. Department of Energy (DOE) sites [1]. DU is the largest mass of nuclear material in the DOE inventory. This material, mostly in the form of DU hexafluoride (DUF_6), resulted from gaseous diffusion plant operations at Oak Ridge, Tennessee; Portsmouth, Ohio; and Paducah, Kentucky. The inventory of DUF_6, which is stored in large cylinders aboveground, is increasing at a rate of ~20,000 MT/year.

On August 29, 2002, DOE awarded a contract to Uranium Disposition Services, LLC, to convert the DUF_6 to a stable form and to dispose of any portion that might not be reused. The contract includes conversion facility design and construction; operation of two facilities located at enrichment plant sites in Portsmouth, Ohio, and Paducah, Kentucky; transportation of any portion of the product not destined for reuse; and disposal of that portion. The contract also includes near-term surveillance and maintenance of the DUF_6 cylinder inventory and shipment of the DUF_6 cylinders from Oak Ridge, Tennessee, to Portsmouth, Ohio, as well as incentives for reuse of the DU. Construction of the facilities will begin by July 31, 2004.

DOE is subject to a number of driving forces that encourage or require reuse of DUF_6 and research and development (R&D) toward this end. In the legal and regulatory arena, Public Law 102-486 [2] requires DOE to prepare a study that identifies DU tailings available for conversion to commercial use. Public Law 105-204 [3] requires that DOE undertake a good-faith effort to consider recycle (i.e., beneficial use) for DU. A Record of Decision was published in August 1999 [4]. In response to this legislation, DOE prepared a document, *Depleted Uranium Materials Use Roadmap* [5], which is a guide to R&D activities. The roadmap builds on the analysis performed and documented in the final *Programmatic Environmental Impact Statement for Alternative Strategies for the Long-Term Management and Use of Depleted Uranium Hexafluoride* [6]. An agreement [7] between DOE and the State of Ohio requires a continuing good-faith effort to find beneficial uses for DUF_6 and the production of annual reports that document progress in this area.

At least as important as the legal/regulatory driving forces is the desire to reduce the cost to the government for disposition of the DUF_6. Although DU has been used historically in applications ranging from munitions to counterweights to radiation shielding, the sum total of these applications would consume only a small fraction of the inventory. As a consequence, DOE is supporting a DU Uses R&D Program to create new uses for DU that might avoid some or all of the costs of DU disposition. The basis for this program is the previously mentioned *Roadmap* [5].

This paper summarizes the current status of the potential for DU uses to reduce the cost of DUF_6 disposition and the areas that are being investigated toward this end. However, none of the potential uses are sufficiently well developed to permit a rigorous economic analysis of the cost-effectiveness of DU reuse. Thus, the economic analysis in this paper will focus on framing the economic basis for reuse, the costs or cost ranges that are presently known, and discussion of uncertainties and possibilities.

BENEFIT TO DOE OF REUSE OF DU

The benefit to DOE of reuse of DU is cost savings. Such savings could be realized in two ways: (1) avoiding some or all of the potential cost to disposition the DU oxide product from the conversion plant by disposal and (2) receiving revenues from the sale of DU.

Avoiding DU Disposition Costs

Initial baseline disposition cost. The baseline approach for disposition of any unused DU oxide (primarily U_3O_8) conversion product is to package it in suitable containers and transport it from the conversion plants to the Nevada Test Site (NTS) or to Envirocare of Utah for near-surface disposal. The cost of disposing of the entire 500,000 MT inventory of DU as oxide at NTS was estimated [8] before the conversion contracts were awarded; the results are summarized in Table II.

Table II Estimated Cost for Disposition of DU Oxide Inventory at the NTS

Disposition Cost Component	Estimated Range of Cost, $M
Packaging	93B170
Transportation	88B160
Disposal	60B100
Total	241B430

The results cover a range of values because the number of containers required depends on the bulk density of the DU oxide product, which can range from 1.5 to 4.0 kg/L, depending on the conversion and packaging techniques used.

Optimized baseline disposition cost. Initial systems studies by the conversion contractor identified the opportunity to reduce the baseline disposition cost of the DU oxide product shown above by shipping the product to Envirocare=s disposal facility in Utah. This significantly reduces the disposition cost in three ways. First, rail shipment can be used at Envirocare whereas more costly truck shipment is the only means to access NTS. Second, the weight of a single package is limited to 430 kg at NTS whereas Envirocare can accept much larger packages (up to the size of an entire railcar). Third, container costs are reduced by the use of emptied DUF_6 cylinders to package the DU oxide product. Updated cost estimates have not yet been released but are believed to have a value in the $150B$200M range.

To the extent that beneficial uses are found for DU, the cost of disposition can be avoided by having the user take custody of the DU at the loading dock of the conversion plant. The DU product that is likely to be useful to potential users is uranium dioxide, which will require limited additional processing in the conversion plant to uniformly reduce the uranium to the +4 valence state. However, this step constitutes existing technology in nuclear fuel fabrication plants and is not expected to increase costs significantly.

Upper-bound baseline disposition cost. An important assumption in achieving the disposition cost described in the preceding section is that near-surface disposal of the DU oxide product is acceptable. This determination will be made as part of the National Environmental Policy Act (NEPA) process involving issuance of site-specific draft environmental impacts statements; soliciting comments thereon; and reconciling the comments, leading to a record of decision. The validity of this assumption is supported by the fact that various forms of DU from multiple DOE facilities have been disposed of at the Envirocare facility over a period of years. However, the validity of this assumption could be called into question for two reasons. First, the amount of DU involved in converting DOE=s entire inventory is much larger (at least 10 times greater) than that of all the DU previously disposed of. Second, the U.S. Nuclear Regulatory Commission is on record [9] as questioning the acceptability of near-surface disposal of DU at an enrichment plant that was proposed to be built in Louisiana. However, the applicability of this position to arid sites in the western United States is unknown.

If more confining disposal of the DU product were required, the baseline disposition cost could increase substantially. Estimates for more elaborate measures such as use of a consolidating matrix such as grout, use of engineered subsurface structures similar to concrete bunkers, or the requirements for disposal in deep mines or subsurface excavations have been estimated and range up to about $1500M [10].

Potential Revenues from Sale of DU

None of the potential uses of DU are yet sufficiently mature to assess their worth to the users with sufficient accuracy to allow potential revenues to be evaluated. Such worth could result from two sources. First, DU-based products could substitute for more expensive components. One example of this is substituting a DU-based geochemical barrier for repository waste package components presently composed of expensive degradation-resistant alloys such as titanium and Alloy C-22 (a high-nickel alloy). If the DU-based barrier can be substituted for the metal barriers without compromising protectiveness or causing other unacceptable impacts, then the metal barriers, which are estimated to cost $5B [11] might be eliminated while simultaneously using the entire DU inventory. Thus, in this application, the DU could be worth up to $10/kg DU ($\$5 \times 10^9 / \$5 \times 10^8$ kg DU), although the fabrication cost of the DU-based barrier must be subtracted to establish the unit breakeven worth of DU. Using natural uranium in this application would not be economic, because, even in the presently depressed market, it sells for $20B$40/kg U. It is noteworthy that at $5/kg DU (net costs, allowing for fabrication), the revenues (cost avoidance by the repository program) from this application would be sufficient to pay the life-cycle cost of the entire DUF_6 conversion project.

A second potential economic advantage of DU is based on capitalizing on properties of uranium such as its high density and complex electronic structure to yield products having improved or even unique capabilities. One example of this is the use of DU-based materials of construction such as DUCRETEJ or a DU-steel cermet for spent fuel storage and transportation casks. The high density of these materials could result in reduced costs in two ways. Fewer shipments would be required (because each cask has a higher payload), and fewer casks would be required (because a separate transfer cask would not be needed to move spent fuel from water pools into dry storage at nuclear reactor sites) [9]. In addition to potential economic benefits, the use of such materials may offer nonquantifiable benefits such as increased resistance to accidental or deliberate breaching forces and reduced occupational dose from spent fuel transfer operations. Another example is the potential for DU dioxide to be used in semiconductor applications, such as in the manufacture of computer chips. The refractory nature of DU dioxide would yield a chip capable of withstanding high temperatures and also the high radiation fields typical of space applications. The magnitude of these benefits has not yet been estimated.

BENEFICIAL USES OF DU

A number of beneficial uses of the DUO_2 conversion plant product have been identified. Such uses can be divided into two groups: (1) those that consume the entire surplus DU inventory and (2) those that consume only a fraction of the inventory. High-volume uses [e.g., as new shielding materials for spent nuclear fuel (SNF) casks and as additional chemical barriers at geological SNF disposal sites] capitalize on the density and chemical identity of DUO_2. These uses are all in radiologically regulated applications.

High-value beneficial uses of DU capitalize on unique electronic properties of uranium. Examples of such uses would be in semiconductors, electrodes in batteries, and fuel cells, as well as in electrolysis of water to produce hydrogen, and in catalysts. These uses would be predominantly in radiologically unregulated areas. The benefits would be the potential for products having unique capabilities and significant revenues, if the appropriate application could be found.

High-Volume Uses

Repository Uses. The preponderance of SNF destined for disposal under current U.S. policies is Zircaloy-clad, low-enriched uranium dioxide fuels from light-water reactors. The resistance of the SNF disposal cask depends upon interaction of hot groundwater and humid air with the SNF and engineered barrier system over time. The SNF could be contained in a package composed of DUO_2-based engineered barriers. If this is done, the chemical interaction of water and air with the DUO_2-based barriers should create conditions that delay water and air penetration to the spent fuel and reduce radionuclide release rates thereafter. Two approaches are envisioned: (1) filling the void spaces in the container with DUO_2 in a sand-like form and/or (2) building the SNF basket and/or package walls with a material made from DUO_2 cermet. The fill concept consists of inserting DUO_2 particles into a repository disposal package, completely filling the gap between fuel rods and between fuel assemblies. Such use is thought to have the potential to reduce (1) the rate at which groundwater might reach the fuel, (2) the dissolution rate and solubility of the fuel matrix, and (3) the diameter and weight of the overall package needed to achieve a specific dose rate. The DUO_2-steel cermet concept consists of DUO_2 particulates embedded in a continuous steel phase. Typical cermets use sandwich construction with clean uncontaminated steel layers on both sides of the cermet. It is envisioned that DUO_2-steel cermets could replace some steel components of a waste package shell and basket. The presence of DU should also reduce the likelihood of a criticality event over geologic time by lowering the average ^{235}U content. DUO_2 metal barriers could conceivably replace some of the $5B of engineered barriers at the geologic repository.

Research is being conducted to elucidate the nature and rate at which DUO_2, steel, groundwater, and air interact as a basis for determining whether DU-based engineered barriers can be substituted for other, more expensive barriers. If this appears promising, additional studies will be initiated to examine the impacts of DU-based engineered barriers on waste package and repository performance.

Shielding Applications. A large potential market for DU is in radiation shielding applications. Although DU metal has been used in such applications, its relatively high cost can be justified only when the need for high-density shielding offsets this cost. However, DU oxides (primarily DUO_2) could be used as a component of the primary shielding material in containers designed to store and, in some cases, dispose of SNF or high-level radioactive wastes. The high density of uranium compounds makes them excellent components as shields from photon radiation.

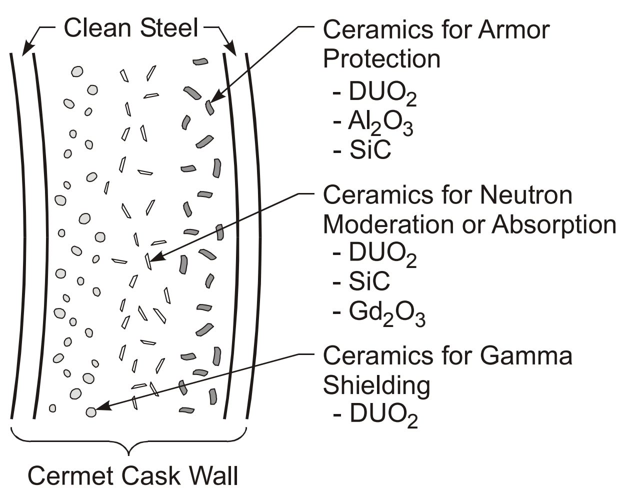

Fig. 1.

Two new uranium composite materials are envisioned for SNF storage and transport casks. One attractive new DU shielding material involves making a Aheavy@ concrete (e.g., DUCRETEJ), using a high-density DU compound as one of the components. If a DU compound is used to make the concrete, the same shielding performance could be achieved with up to one-half the thickness required of normal concrete, depending on the form of the DU [2]. To provide predictable structural strength, in this approach, the uranium compound is substituted for the coarse aggregate in conventional concrete and is enclosed between annular stainless steel shells that make up the body of the container.

The second new shielding material is DUO_2-steel cermet. Cask shells would be constructed of a cermet of DUO_2 particulates embedded in the steel, which in turn, would be contained between clean layers of steel (see figure). Because of the higher oxygen content associated with DUO_2, which moderates neutrons, cermets also have better shielding capabilities than steel. The cermet could also include a neutron absorber, such as gadolinium, for efficient absorption of neutrons.

There are ~131,000 pressurized-water reactor and 175,000 boiling-water reactor fuel assemblies that will be produced by U.S. nuclear power plants under the terms of their current licenses. Approximately 10,000 casks will be required for the storage and transport of commercial spent fuel to the repository [12]. It is estimated that 50–60 MT of DU will be required per cask to produce the "new generation" of DU casks to be used for spent fuel storage, transport, and disposal. The containment of DU composites within 10,000 casks that can be used in the United States alone will require the use of the total DOE DU inventory. The cost of material purchase and fabrication for conventional casks is in excess of $6B. The cost to procure materials for the fabrication of spent fuel and high-level-waste (HLW) containers within the engineered barrier at the geologic repository is estimated to be in excess of $14B. If DU composite materials can provide advances in radioactive material shielding and structural performance of casks, the estimated U.S. container cost of ~$14B can be significantly reduced using more uniform DU cask designs. The revenue from sales of DU casks is estimated to be as much as $0.5B/year.

Ongoing R&D is focused on confirming the long-term stability of candidate heavy concretes and on developing low-cost manufacturing techniques for large cermet shapes.

HIGH-VALUE USES

The DUF_6 Materials Use Roadmap [5] identifies the need for a science program to conceive and develop new potential uses for the DU conversion product. This need has led to the identification of a number of ideas that appear to be promising but where fundamental questions remain concerning the scientific feasibility. If only one or two of these potential uses were to prove feasible, a high-value market for DU could result, with attendant cost savings. Research is being conducted to ascertain the scientific feasibility of some of these high-value uses.

Uranium catalysts

U.S. industries and DOE must manage a variety of off-gas wastes consisting of complex volatile organic compounds. Ongoing research concentrates on a new class of nanoporous uranium oxide sol-gel catalysts doped with uranium oxides for destruction of a range of volatile organic contaminants, including alkanes, aromatics, and chlorinated organic compounds. Proof-of-principle experiments have been conducted, and optimal formulations are being sought. If performance meets expectations, uranium-based catalysts might replace high-cost platinum-based catalysts. The U.S. catalyst market is estimated to be ~$9B in 2003. Thus, a small niche in this market could be lucrative.

Uranium-based semiconductors

Uranium oxides have electrical and electronic properties that are equivalent, or superior, to those of conventional Si, Ge, and GaAs semiconductor materials. Thus, it appears that a new, higher-performance class of semiconductors is possible: uranium oxide–based semiconductors. Uranium oxides have characteristics that could give them significantly better performance than conventional semiconductor materials: operation at substantially higher temperatures and greater radiation and electromagnetic force resistance, qualities that could make them more suited for use in hazardous environments. A number of urania semiconductor devices are possible, including solar cells, thermophotovoltaic cells, and thermoelectric cells, as well as diodes and transistors. The semiconduction properties of solid-crystal DUO_2 with various dopants have been measured. A uranium-based diode and transistor have been constructed and tested. Replacing current silicon chips with DUO_2 chips would consume ~30,000 MTU/year. Assuming $20/kg U, this translates to more than $0.5B/year in revenues.

Urania fuel cells

Current solid oxide fuel cell (SOFC) technology is limited by relatively poor ion conductivity, erosion of electrodes and electrolyte due to surface interactions, and differences in thermal expansion of different materials at the electrode/electrolyte interface. Stabilized uranium oxides promise solutions to these problems. It is believed that stabilized uranium oxide films will be superior electrodes for SOFCs because of their higher mixed (electronic/ionic) conductivity, better stability, and improved structural compatibility with solid electrolytes. This work will lead to substantially improved components for SOFCs. The dollar value of a more efficient fuel cell is not estimated. The U.S. fuel cell market is estimated to be ~$12.6B in the year 2012.

Photoelectric hydrogen production

Photoelectric cells (PECs) are devices that provide a direct method for converting optical energy into either chemical or electrical form. In the case of conversion of optical energy into a chemical form, light strikes the PEC anode, resulting in the photoassisted dissociation of water into hydrogen and oxygen, thereby providing hydrogen fuel that can be stored and utilized at a later time. A number of semiconducting materials have been suggested for use as PEC anodes for the dissociation of water. However, electrode stability has proven to be a crucial problem in the realization of a workable PEC device. The most promising oxides that have been identified include pure UO_2 and uranium-doped potassium tantalite. The dollar value of a more cost-effective method of producing hydrogen has not been estimated. The hydrogen economy is currently about $2.5B/year and growing at a rate of 10%/year.

INTERNATIONAL COLLABORATIONS

The DU Uses R&D program engages in collaborative international activities to better understand the international situation concerning the disposition of DUF_6, provide credibility to U.S. efforts to beneficially use DU, and obtain the benefits of lower-cost or cost-shared research results. Currently, extensive collaborations are being conducted with the Russian Academy of Science and with Minatom.

CONCLUSIONS

The cost-effectiveness of using the DU oxide conversion product from facilities to convert DUF_6 to a more stable form depends on the magnitude of the avoided DU oxide disposition cost and potential revenues from the sale of DU-based products. The packaging, transportation, and disposal costs are expected to range from $150M to $200M but could be much higher if more elaborate waste forms or disposal technology were to be required. It is not yet possible to accurately estimate the revenues resulting from potential DU uses, which could consume a substantial portion of the DOE inventory. However, success concerning the better-developed potential applications related to spent fuel storage, spent fuel and waste transportation, and the repository could reduce or avoid costs measured in billions of dollars. Revenue from sale of casks made of DU composites could be as much as ~$0.5B/year. Other potential uses of DU still in the fundamental research stage might add substantially to this total if they are proven. The U.S. government has an ongoing program to investigate such uses and to develop the most promising of these technologies to the point that they are available for deployment.

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FOOTNOTES

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