

BREAKING DOWN THE BARRIERS TO THE BENEFICIAL REUSE OF DEPLETED URANIUM

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ABSTRACT

The U.S. government has accumulated approximately 700,000 tons of depleted uranium. This is the result of over 50 years of enrichment operations that produced nuclear reactor fuel and material for nuclear weapons. This depleted uranium, sometimes called "enrichment tails," is stored as pure uranium hexafluoride in steel pressure vessels. The U. S. Department of Energy is actively considering strategies for its long-term management.

Recent federal legislation (Public Law 105-204) directs the Department to include a request for almost \$400 million in its fiscal year 2000 budget. The funds are to be used to start construction of two depleted uranium hexafluoride conversion facilities. The legislation does not specify what the depleted uranium hexafluoride is to be converted to or the purpose of conversion.

If the purpose is to prepare the material for disposal, \$400 million is a minor part of the \$3 billion to \$4.5 billion required. On the other hand, conversion could instead prepare the enrichment tails for reuse by private industry. Sales of the conversion products would offset government costs for management of the material. In addition to this benefit, the feedstock would result in new industrial facilities and long-term, well-paying jobs. This paper proposes that the enrichment tails be converted to forms suitable for industrial use, and that the government take specific steps to encourage this reuse.

The market potential for depleted uranium metal, compounds, and alloys is extraordinary. This paper provides some data collected by the government to illustrate this potential.

Technical and institutional barriers have prevented development of a market for depleted uranium. To overcome these barriers, we propose creation of a center to encourage industrial reuse of the enrichment tails. This center would: (1) evaluate existing data, (2) develop and test new uranium materials, (3) incorporate uranium materials data into engineering codes and standards, (4) work with the U.S. Nuclear Regulatory Commission to assure that a proper regulatory structure exists, and (5) work with industrial partners to encourage depleted uranium use. Recently, Ohio State University and the University of Kentucky submitted a proposal to the U.S. Department of Energy to create such a center. The universities propose creation of the *Midwest Institute for Depleted Uranium Solutions* (MIDUS).

BACKGROUND

Depleted uranium is the by-product of the uranium enrichment process. Naturally occurring uranium typically consists of 99.3% non-fissile ^{238}U and only 0.7% fissile ^{235}U . To be useful as a nuclear fuel or as a weapon, the fissile content of the uranium must be increased. The process of increasing the fissile fraction of uranium is called enrichment. The enrichment process generates substantially more depleted uranium than enriched product. The concentration of fissile ^{235}U in depleted uranium is generally reduced to around 0.2%.

The U.S. government has been producing enriched and highly-enriched uranium for over 50 years and as a result has accumulated approximately 700,000 tons of depleted uranium. Most of this material is in the form of uranium hexafluoride and is stored in cylinders at the DOE enrichment sites located in Paducah, KY, Portsmouth, OH, and Oak Ridge, TN. The current depleted uranium hexafluoride management program was created to select and implement a long-term management strategy for this material. A Draft Programmatic Environmental Impact Statement (PEIS) (1) has been completed to analyze the various options for disposition of the depleted uranium. Preliminary cost studies indicate that conversion and disposal of the entire inventory would cost \$4.5 billion or more. The preferred alternative in the Draft PEIS is to consider the material as a resource and to use it in beneficial applications. This preferred alternative is also consistent with an agreement between the DOE and the State of Ohio to seek reuse of the depleted uranium materials within the next ten years (2).

A small market for the use of depleted uranium metals and alloys in counterweights and armor-piercing kinetic energy projectiles exists, but is not likely to consume the entire inventory (3). The DOE-preferred alternative is to encourage the growth of this market by working closely with the industries that will fabricate and use depleted uranium and its compounds in key industrial applications that capitalize on uranium's unusual properties. A cooperative program containing five elements is proposed:

Declassification and Publication of Information: Much of the information about the material properties of uranium metal, compounds and alloys was originally classified. DOE has declassified a large body of this information and is taking steps to make it available to the engineering community at large.

Proper Regulation: Since uranium is slightly radioactive and toxic it is important that its use be properly regulated. Market decisions must consider involvement by the U.S. Environmental Protection Agency, and the U.S. Nuclear regulatory commission.

Industry Outreach: Ultimately, any use for uranium will be implemented by industry. It is necessary to provide information to and get suggestions from industry to nurture depleted uranium applications.

Research and Development: The DOE has developed Many uranium-based metals and compounds. However, they were developed for purposes other than providing a material having commercial value. Further development will be necessary to support industrial applications.

The Russian Experience: For identical reasons, the Russian government also has extensive inventories of depleted uranium. International cooperation would provide us with the

benefit of Russian experience, and improve the potential for high-paying, non-weapons related jobs for Russian nuclear scientists.

INDUSTRIAL USES FOR DEPLETED URANIUM

Uranium metal alloys are strong and ductile and can compete with many specialty metals (4). These alloys have been used in applications based principally on their unique nuclear properties and high density. We plan to assist industry in the development of new products that take advantage of these unique properties.

However, perhaps the most exciting applications for depleted uranium lie in its compounds, particularly its oxides. At elevated temperatures uranium oxide can have an anionic conductivity substantially better than cubic zirconia, currently the material of choice in many oxygen-sensing applications. Its chemical stability at high temperatures makes it an ideal candidate for a component of aluminum manufacturing processes. Catalytic applications of uranium oxides are extremely promising and could consume large quantities (possibly all) of the existing reserves.

Surprisingly, the use of depleted uranium in industry can actually save lives. Many industrial accidents involve equipment simply tipping over due to a lack of effective counterweights. OSHA estimates that there are about 85 such deaths/year involving forklifts alone. These industrial injuries and fatalities could be avoided through inclusion of depleted uranium components in the equipment design (6). The proposed center will seek to establish manufacturing facilities at the storage sites to produce these counterweights or structural components to lower the center of gravity of such equipment and improve its stability.

Additionally, conversion to metal or oxide will make fluorine available for reuse. Industries could be constructed at the conversion site to make use of this product of uranium hexafluoride conversion alone. As a raw material for the production of commercially valuable products, the cost of management and disposition of depleted uranium would be reduced.

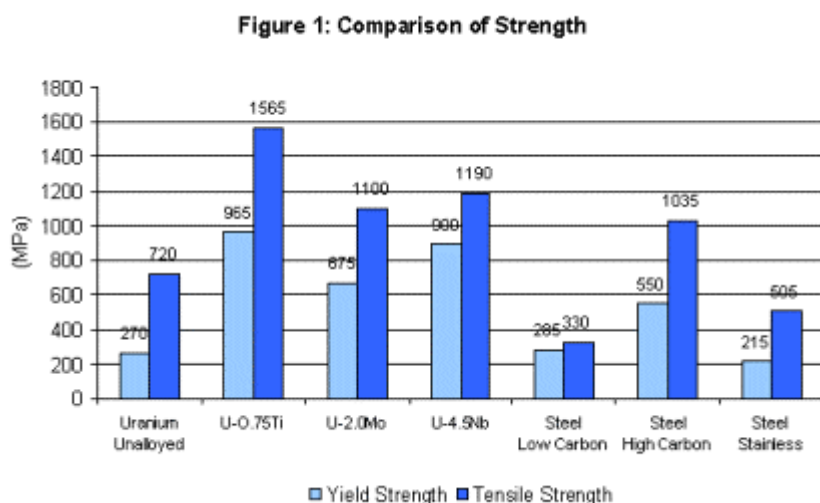
An international market for depleted uranium would help eliminate concerns over international proliferation. The former Soviet Union stockpiled enormous reserves of depleted uranium. Industries based on its peaceful application will provide Russian nuclear scientists with much needed hard cash while employing both weapons complex engineers and workers. Such improvements in the economic well being of these personnel are critical in avoiding the attraction of various criminal activities. In addition, *conversion of depleted uranium metal into oxides or other compounds useful to industry will make utilization by relatively unskilled terrorists nearly impossible*. These factors will help prevent the migration of both Russian materials and technical skills to organizations wishing to develop nuclear weapons capabilities.

MATERIAL PROPERTIES OF URANIUM METAL

Metallic uranium is moderately strong and ductile. It can be cast, formed and welded by a variety of processes. Its chief characteristic that differentiates it from other common metals is its very

high density (19.1 g/cm^3). Uranium is frequently chosen for use over the few other equally dense metals because it is more workable than tungsten and much cheaper than gold or platinum. Uranium metal readily oxidizes in dry and moist atmospheres and is pyrophoric when finely divided. Uranium can be alloyed with other elements to improve strength and hardness and reduce its susceptibility to corrosion. Some alloys have material properties comparable to high-strength specialty metals (4). Some DOE data suggest that uranium alloys might be produced that have greater strength than most known specialty metals (7).

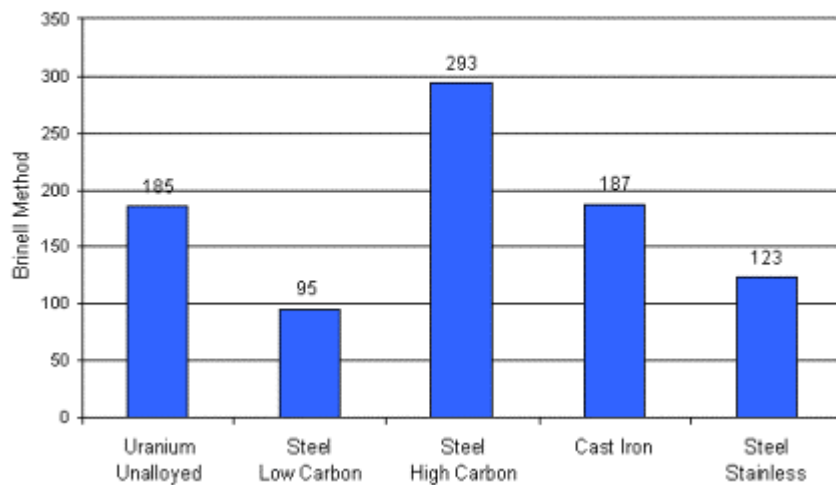
Figures 1 and 2 compare the yield strength, tensile strength, and hardness of uranium and uranium alloys to stainless steel, low carbon steel, high carbon steel, and cast iron. The data used came from the commercial materials information world-wide web site, MatWeb (8) and from the American Society for Metals, Metals Handbook (9).



As can be seen in the figures, yield, tensile strength, and hardness of unalloyed uranium compare quite favorably to other metals. Alloying uranium with small percentages of titanium, molybdenum, and niobium can improve these properties significantly. Some uranium alloys are much less corrosive than pure uranium metal, reducing the hazard associated with ingesting or inhaling it.

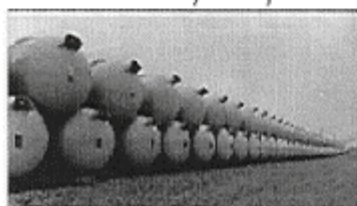
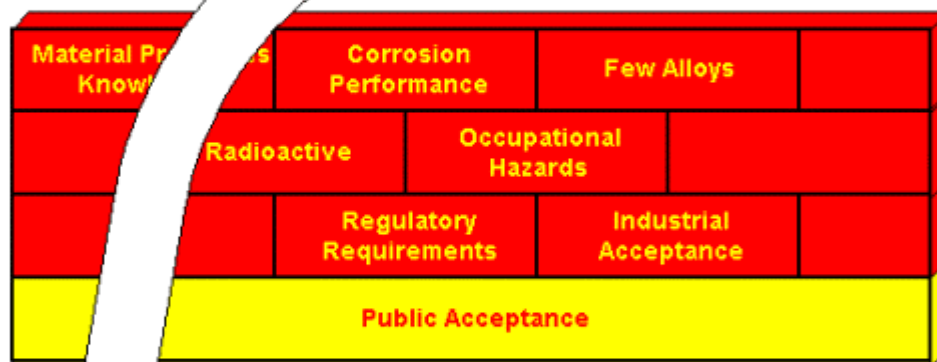
The data presented here only suggest the potential uses of uranium alloys. Existing data must be further evaluated for validity, and more data must be collected to realize the full benefit of uranium.

Figure 2: Comparison of Hardness



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Further, unique electrical and chemical properties of uranium might also be of commercial value. Finally, the data must be incorporated into engineering codes and standards so designers can use the material with confidence.

BARRIERS TO INDUSTRIAL USE

There are a number of technical and institutional barriers that must be overcome before industrial applications can be successfully developed and marketed.

Physical Properties Database

One of the greatest obstacles to wider use of uranium in industry is a general lack of knowledge concerning its material properties. Since the 1940s, extensive research has been performed on uranium metal. However, this early research was done with the view of using the uranium as fuel for nuclear reactors or as nuclear weapons components. While providing a great deal of knowledge regarding certain uranium characteristics, the focus on uranium use as fuel or weapons materials limits the value of the data in making decisions about uranium alloys as structural materials. In the 1970s and 1980s, research into uranium alloys and their properties was intensified as conventional weapons uses were identified for depleted uranium alloys. While originally classified, results of this research are mostly available in the open literature today.

A complete literature search of classified and unclassified uranium properties data should be completed, and the results published for use by government laboratory, industry, and university researchers inside and outside the United States. Where classified data appear promising and the need for secrecy has passed, an attempt should be made to de-classify the information. Recognized professional societies, such as the American Society for Testing and Materials (ASTM), should be encouraged to develop consensus codes and standards for the selection and use of depleted uranium compounds and alloys.

The results of the literature search and new methods of computational materials science should guide preparation and testing of known or new uranium alloys. The literature search should identify the need for new data. "Computational experiments" can then provide extremely cost effective ways of surveying broad regions of the potential alloys that uranium can form. This will allow experimental verification to be focused on a limited number of alloys that are computationally predicted to have properties of potential commercial interest, dramatically reducing the extreme costs of a trial and error exploration program.

Radioactivity and Other Occupational Hazards

Depleted uranium is only mildly radioactive and is listed as a low specific-activity material in shipping regulations. The primary radiological hazards associated with this material are beta and alpha emissions. The dose rate of this modestly penetrating radiation decreases dramatically with distance from the source due to absorption in the air and geometric effects. As a result, working near depleted uranium and normal handling of this material does not result in excessive

exposures. Nonetheless, significant exposures could result from continuous very close contact, so unnecessary direct contact should be avoided.

Alpha radiation is also emitted by depleted uranium, but this non-penetrating radiation is not a hazard unless the finely divided uranium particles become airborne and are inhaled where the alpha radiation can damage sensitive lung tissue. Hence it is important to ensure that airborne concentrations remain below the OSHA standard of 0.25 mg/m³ of air.

Depleted uranium is about as chemically toxic as other heavy metals such as lead, and must not be ingested. Problems can best be avoided by careful control of any finely divided material and by good personal hygiene.

Finely divided uranium metal is pyrophoric; therefore machining chips and grinding residue must be handled carefully to avoid the danger of fire. These hazards can be minimized by keeping machining waste submerged in water or oil, removing chips from tools and work areas frequently, and avoiding mixed metal chips. Dry powder fire extinguishers should be readily available. Water should never be used on uranium fires (10).

A substantial reference base on the radiological and toxicological hazards of depleted uranium and some depleted uranium alloys has been developed by DOE and DOD. These data, augmented as needed, can serve as the basis to identify and mitigate occupational hazards faced by industrial reuse of depleted uranium products. Engineering designs and procedures make a substantial difference in contamination control and avoiding unacceptable exposure. Control measures to contain the material within specified bounds may be identified. Conversely, mitigation measures may be developed to ensure no loss of material control or unnecessary personnel exposure. The experience gained by DOE uranium processing sites provides an extensive basis for control and mitigation recommendations. Experience gained from Army use of depleted uranium alloys in munitions manufacture and testing adds relevant and practical information to this data base.

Most of the hazards associated with depleted uranium are more related to the manufacturing of products using depleted uranium rather than the use of depleted uranium in finished products. Because depleted uranium is a radioactive material its use should be confined to the industrial workplace where systems of occupational safety procedures are already in place to manage other workplace hazards and protective control measures for the safe use of depleted uranium products and components could be implemented with minimal impact. The limited exposure risks from depleted uranium products need to be evaluated relative to other occupational hazards already present in the workplace.

Regulatory Requirements

Current NRC regulations specifically deal with “manufacture of industrial products and devices containing depleted uranium . . .” for “the purpose of providing a concentrated mass in a small volume . . .”. The manufacturer must obtain a “specific license” to manufacture counterweights

for general use. He must show that it is unlikely that use of the product is unlikely to cause any individual to receive in one year more than 10% of the allowable occupational exposure (5 rem). While the regulations do not specifically address applications other than ballast, they do provide the basis for including other uses. The DOE should work with the NRC to make sure that regulations support depleted uranium disposition plans.

Industrial Acceptance of Depleted Uranium Products

Industry will be understandably skeptical and wary about the presence of depleted uranium in their workplaces. For the most part, most are unaware of the advantageous properties that depleted uranium presents. An aggressive program of industrial education, involvement and partnering will be required. Such a program must demonstrate four key factors:

1. depleted uranium offers unique material properties that will provide competitive performance or cost advantages and prospects for substantial profit,
2. the occupational hazards associated with the use of depleted uranium are both manageable and small relative to other occupational hazards already present,
3. regulation of depleted uranium will not present an overwhelming burden, and
4. the DOE will be a reliable partner with industry and share in product development.

These industrial partnerships should include direct contact with selected key industrial sectors to present the case for the benefits of depleted uranium.

Public Acceptance

Probably the single greatest challenge to implementing beneficial industrial applications with depleted uranium will be overcoming the general public fear of radioactivity. An effective public outreach program must be established early in the program to educate the public on the real risks and benefits of using depleted uranium for industrial applications. An educated public will be better able to evaluate specific use applications based on tangible merits rather than abstract fear. The public outreach effort will be a gradual, long-term process and needs to be started well in advance of introducing products to the market place. The public outreach efforts need to be conducted by parties that will be seen by the public as credible and objective.

OVERCOMING THE BARRIERS TO BENEFICIAL USE OF DEPLETED URANIUM

A concerted effort by a team of technical experts, researchers, industrial partners, and local stakeholders will be required to overcome obstacles to developing depleted uranium markets. This paper recommends establishment of the university-based *Midwest Institute for Depleted Uranium Solutions* (MIDUS) to achieve this goal (Figure 3).

The Institute would combine a) the technical capabilities of the Ohio State University, University of Kentucky, and the national laboratory system with b) the stakeholder perspectives of the enrichment site communities and c) the market needs of industrial partners. This will create a focal point for materials research and industrial product development.

The purpose of the Institute should be to:

- direct and implement research on material properties of uranium compounds,
- create new uranium compounds having tailored properties valuable to industry,
- foster partnerships with private industry to develop new uranium products,
- develop appropriate uranium product manufacturing processes,
- identify, evaluate, disseminate data on material properties,
- research the environmental, safety and health aspects of uranium products, and
- establish a public outreach program regarding beneficial use of depleted uranium.

Performance Objective

By the end of the ten year development period provided in the enforceable consent agreement between the DOE and the State of Ohio (2008), the MIDUS will have sufficiently developed a series of potential depleted uranium products and markets to validate the current strategies to convert the inventory to beneficial uses.

Performance Measures

The MIDUS will focus on transforming the state of depleted uranium from the current paradigm of significant financial liability, limited knowledge, small existing markets, and few industrial partners to a commercial environment more conducive to beneficial reuse of the depleted uranium stockpile. Performance measures must be components of the desired end state of the depleted uranium business environment. Figure 4 illustrates the global mission of MIDUS, as well as its interdisciplinary nature.

Research and Development in the Midwestern Institute for Depleted Uranium Solutions



Uranium compounds and alloys have been used in applications based principally on their unique nuclear properties and high density. These applications include nuclear fuels and weapons, armor/anti-armor, counterweights, inertial components, and radiation shielding. The material requirements for these applications are relatively unique and in some cases highly guarded. The general knowledge of the properties of uranium materials has been limited, not because the materials are classified but because the materials development was supported by sensitive applications.

In general, there is no consistent set of material properties for uranium compounds and alloys. This is because much of materials development was done for specific applications with limited mechanical property requirements (e.g., weapons, fuels) and before the establishment of uniform standards for testing materials. The first major application (and largest use to date) that began to exploit the mechanical properties of uranium alloys was for large-caliber kinetic energy projectiles. Here again the driving force was high density combined with mechanical properties adequate to drive the projectile out of the gun. The vast majority of recent materials development for non-nuclear applications supported this application. While a great deal of good work was done, the density requirements of the application demanded that only lean uranium alloys (e.g., U-3/4% Ti) be considered. Materials development to support government applications has resulted in a class of materials that can be represented by the following:

- Unalloyed uranium
- Uranium - 3/4 wt % titanium
- Uranium - 2 wt % molybdenum

Uranium - 6 wt % niobium

Many other alloys were studied but not used beyond the weapons program (7).

A broader examination of compounds and alloy compositions for commercial applications is absolutely required to encourage industrial participation in the program to develop reuse applications of the stockpile. The MIDUS will develop and implement a research strategy to create new compounds, establish a comprehensive set of materials properties, further advance thermo-mechanical processing of depleted uranium alloys to improve strength and ductility, develop improved coating technologies to reduce corrosion, develop efficient and safe fabrication technologies, and assist industry in the development of new products that take advantage of the unique properties of depleted uranium alloys.

It is vitally important that industry be involved in the R&D effort. Only through this will realistic products and markets be established to recover the intrinsic value of the inventory and offset the management costs.

Research and Development Strategy

The goal of the R&D effort is to define uranium compounds and alloys with properties that are relevant for commercial applications at competitive costs. A strategy will be established to demonstrate that uranium materials have properties that are useful for commercial applications and can be produced at reasonable costs.

The R&D Strategy will consider the following factors:

Material Properties Research. There is a compelling need to develop a consistent set of material properties for the four representative uranium alloys (i.e., unalloyed, U-3/4Ti, U-2Mo, and U-6Nb) that can be shared with industry. There is currently no good source book on materials selection for uranium alloys. This source book should include mechanical, corrosion, wear, electronic, thermal, and electrochemical properties of these alloys under realistic conditions. It is important to note that there is a great deal of data in the literature on these materials that could be used to populate the source book. However, much of the information is application-specific or of sufficient age that accepted standards may not be used in the data collection. A notable exception is the extensive database developed for U-6Nb at Rocky Flats. The U-6Nb database would serve as a good format for the other materials.

Alloy Development. The focus of the alloy development will be improved mechanical properties (i.e., strength, ductility, fracture toughness, stress corrosion cracking); corrosion and wear resistance; electronic, thermal, and catalytic properties.

Ceramic Applications. perhaps the most exciting applications for depleted uranium lie in its compounds, particularly its oxides. At elevated temperatures the oxide can have an anionic conductivity substantially better than cubic zirconia, currently the material of

choice in many oxygen-sensing applications. Its stability at high temperatures makes it an ideal candidate for a key component of aluminum manufacturing processes. Catalytic applications of uranium oxides are particularly promising and could consume large quantities (possibly all) of the existing reserves. The 5f electrons present in the oxide combined with their easily reducible nature is expected to produce a compounds suitable to the catalysis of a variety of processes such as:

Steam reforming of natural gas - $\text{CH}_4 + \text{H}_2\text{O} \rightarrow 3\text{H}_2 + \text{CO}$. Since uranium oxides are fairly refractory, they should be able to withstand the high temperatures and pressures required for this application. Determining how and when phase changes occur would be very important, however.

Water-gas-shift (WGS) - $\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$. The reducible nature of uranium oxide makes it a good candidate for WGS catalysis, especially if low loadings of a precious metal (such as platinum) were added.

Preferential oxidation - $\text{H}_2 + \text{CO} + \text{air} \rightarrow \text{H}_2 + \text{CO}_2 + \text{N}_2$. The reducible nature of uranium oxide should allow it to perform in this application.

Thermo-Mechanical Processing. Uranium alloys with exceptionally high strengths (300 ksi) and reasonably ductility (10% elongation) have been developed using thermal-mechanical processing (7). Thermal-mechanical processing of the highly anisotropic materials will lead to uranium alloys with unique strength properties; therefore, thermo-mechanical process development needs to be an essential element of the development strategy.

Coatings Technology. The protection of uranium alloys from the environment and protection of people and facilities from contamination can be addressed by the development of coating technologies. A great deal of work has gone into this topic for some of the limited applications developed for the DOD. This task will further develop both what was done for the DOD, as well as consider solutions that were not appropriate for those limited applications.

Fabrication Technology Development. The focus will be on the development of fabrication technologies to meet specific industrial needs. The foreseeable primary industrial use of uranium alloys is for structural applications, and the two main semi-fabricated forms are extruded products and rolled plate. Initially, these would be the two areas to focus on for advanced processing development. Other areas of process development would be in net-shape forming of components through powder metal technology and other hot working advanced processes. The most promising applications for the oxide are as electrical anodes and catalytic materials. Safe processing technology such as off-gas control, particulate generation minimization and recycle, off-gas particulate measurement and process control, and development and testing of processes for protective coatings will also be developed.

CONCLUSIONS & RECOMMENDATIONS

The U.S. government must disposition its stockpile of approximately 700,000 tons of depleted uranium. The only way to avoid some or all of the \$4.5 billion cost of disposal is to develop marketable products from the depleted uranium.

The benefits of developing beneficial uses for the depleted uranium stockpile include:

- substantial reduction or elimination of this anticipated financial liability,
- create self-sustaining private sector industries in the enrichment communities, and
- help solve issues involving international proliferation of nuclear weapons.

A small market already exists for uranium metal using its high density for shielding and counterweights. If the commercial market for uranium metal is to grow, the DOE must encourage incorporation of uranium compound and alloy properties into engineering design standards and handbooks. The current state of knowledge concerning the material properties of depleted uranium metals and alloys is insufficient to support wide-spread development of industrial products. The DOE needs to invest now in fundamental properties research, industrial partnership building, new alloy development, and early product development.

It must be recognized that private industry is unlikely to accept the business risk of developing depleted uranium products and markets unless DOE invests in the initial fundamental properties research and demonstrates a commitment to partner with industry through the product development phase. The initial investment by DOE necessary to obtain industry commitment to produce depleted uranium products would be small compared with the possible \$4.5 billion cost of disposal.

The time for DOE to invest in depleted uranium product development is now! The typical product development time line is on the order of 5-10 years. If commercial markets are expected to be in place concurrent with the completion and operation of the depleted uranium hexafluoride conversion facilities, it is essential for R&D and product development activities to begin immediately. It is also imperative to better understand the final depleted uranium products and market demand as early as possible so as to best influence the design and throughput of the conversion facilities. The current baseline plan will construct two depleted uranium hexafluoride conversion facilities. If a substantial portion of the stockpile will ultimately be used as a metal or an alloy, these specifications need to be included in one or both of the conversion facility designs. Finally, the enforceable agreement between the Ohio EPA and DOE (Director's Final Findings and Orders) requires the DOE to "...make good faith efforts to evaluate potential use or reuse of the depleted uranium hexafluoride." Only credible investments in material properties research and depleted uranium product development can achieve the spirit of this requirement. If the DOE fails to live up to this requirement, the Ohio EPA can enforce its claims that the depleted uranium hexafluoride is a RCRA waste. A RCRA enforcement environment will add billions of dollars to the cost of this program.

The establishment of a university-based MIDUS would be the most cost effective strategy to focus the government's effort to develop depleted uranium products. The Institute would benefit from the objectivity, creativity, and credibility of the academic community and would have access to the technical capabilities and research facilities of two major university systems and the DOE national laboratory complex. A single interface for industrial partners to participate in product development would be created. Finally, the MIDUS would provide a credible forum to communicate to the public the risks and benefits of using depleted uranium in the industrial workplace.

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