Industrial Uses of Depleted Uranium

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DEPLETED URANIUM (sometimes referred to as DU) is a by-product of the process by which the fissionable isotope U-235 is extracted from natural uranium, and thus can be considered a by-product of the nuclear industry. From an engineering standpoint, the most singular property of uranium is its great density—almost twice that of lead, and nearly as great as those of gold and tungsten. Because of this high density, thin layers of uranium are capable of absorbing as much penetrating radiation, such as gamma rays, as could be absorbed by much thicker layers of less dense metals such as lead and iron.

Uranium is much easier to fabricate than dense metals such as tungsten and rhenium, and is much less costly than heavy metals such as gold and platinum. These qualities make uranium a good candidate for objects that must be small, yet very heavy for their size. Depleted uranium is relatively abundant and available. Consequently, industrial non-nuclear usage has increased steadily during recent years.

Applications

There are three principal non-nuclear uses of depleted uranium: radiation shielding; counterweights in airplanes, helicopters and missiles; and armor-piercing projectiles for military ordnance (Ref 1 and 2). Unalloyed uranium is used mainly in shielding and counterweight applications. Heat treated uranium alloys are used in ballistic or armor-piercing ordnance applications. Besides these three chief uses, depleted uranium has been used in several specific applications where its combination of great density, good fabricability and relatively good mechanical properties give it an advantage over alternative materials.

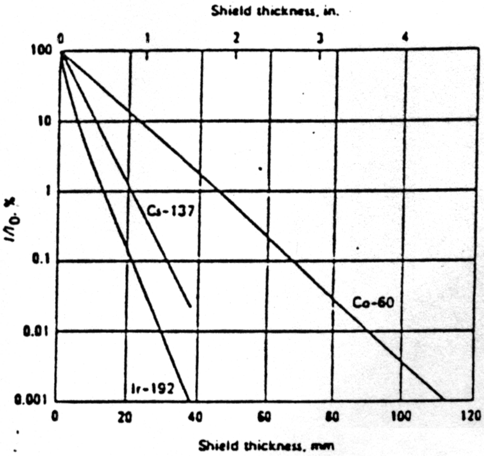
Radiation Shielding. Shipping containers made of depleted uranium are used as spent fuel casks for transportation of highly radioactive spent fuel elements from nuclear reactors to disposal sites. Casks of this type are very heavy (up to several thousand kilograms) and have to withstand and dissipate the heat generated by the spent fuel elements. The uranium containers usually are clad with stainless steel to limit corrosion and contamination.

Containers used in transporting radioactive isotopes for medical and industrial applications are similar in purpose to those used for spent fuel elements, but are much smaller and lighter in weight.

In many devices for medical radiation therapy, depleted uranium is used as shielding against stray radiation from the radioactive isotope inside the device. Depleted uranium is used instead of alternative shielding materials such as lead, which is considerably more bulky, or tungsten, which is more costly and more difficult to fabricate into complex shapes. Uranium can function as both a shielding material and a structural material, greatly reducing the size and improving the mobility of these devices.

Uranium is used extensively in industrial radiographic equipment to house and shield isotope sources such as Ir-192, Co-60 and Cs-137. Two types

Fig. 1 Effectiveness of uranium as a shielding material for three common radioisotopes



Relative intensity of an attenuated beam of gamma rays vs thickness of uranium shield; I is the intensity of radiation on the side of the shield away from the source, and I_0 is the intensity of radiation on the side of the shield toward the source.

of equipment are common. In one, the radioactive source is stationary within the uranium shield, and radiation is allowed to escape by sliding or rotating a uranium plug. In the other, generally known as a "football", the radioactive source moves out of the uranium shield to expose radiographic film. For storage and transportation, the source slides back into the center of the shield through an S-shape tube surrounded by depleted uranium. Motion of the radioactive source is controlled remotely from a safe distance by means of a flexible cable. Figure 1 shows the relation of shielding effect to thickness of depleted uranium for the three gamma-ray sources most widely used.

Counterweights are used in aerodynamic control devices of airplanes, missiles and helicopters to maintain the center of gravity when such devices are moved. Counterweights frequently are complex in shape to fit control-surface contours. High density is important in order to keep the counterweight small compared to the control surface. Depleted uranium is well suited for this application, and uranium counterweights have been used in many civilian and military aircraft. For example, 1500 kg of uranium counterweights are used in each Boeing 747.

Armor-piercing Projectiles. Kinetic-energy projectiles constitute by far the largest single use of depleted uranium. In addition to high density, depleted uranium alloys offer high penetrator effectiveness against single and multiple targets, postpenetration pyrophoricity, ease of fabrication, abundant availability and low cost.

Two alloys, U-0.75 and U-2Mo, are used for penetrators. Penetrators are heat treated to obtain the best possible performance against specific targets. Each of the three military services has one weapons system employing depleted uranium penetrators. The U. S. Navy uses the Phalanx penetrator (U-2Mo, weighing about 0.07 kg) to defend against ship-to-ship missiles; the Air Force uses the GAU-8/A penetrator (U-0.75%Ti, weighing 0.272 kg), which is intended to be fired from A-10 aircraft against armored tanks, and the Army uses the XM774 penetrator (U-0.75Ti, weighing about 3.3 kg) in projectiles for the 105-mm battle-tank gun. Other ordnance applications are under development.

Oil-well Sinker Bars. Depleted uranium is used extensively in oil-well logging. Heavy uranium weights encapsulated in steel (sinker bars) are used to help lower logging instruments into oil wells against the dense, high-pressure fluids present in these wells. Again, the high density of uranium is important so that sinker bars are small but heavy.

Other Applications. Depleted uranium alloys have been used for special high-performance gyroscope rotors. A gyroscope rotor having a U-8Mo rim and a lightweight beryllium hub has been produced and tested with satisfactory results. Depleted uranium flywheels have been produced for large inertial energy-storage devices. Uranium also has been used for vibration damping, especially in boring bars and machine tools.

Properties of Depleted Uranium

Uranium is an allotropic metal having three phases in the solid state. Below 688 °C, the metal is in the alpha phase (orthorhombic), which exhibits increasing ductility from room temperature to the phase-transformation temperature. From 688 to 775 °C, the metal is in the beta phase (tetragonal), which is brittle and unworkable. From 775 °C to the melting point, it is in the gamma phase (body-centered cubic), which exhibits great ductility and very low strength.

Uranium is a highly anisotropic material. Properties can vary extensively, depending on fabrication history and orientation with respect to the direction of working. Impurities such as carbon, iron, silicon and aluminum have strong effects on mechanical properties. The properties given in this section are typical of production material for unalloyed depleted uranium of standard purity and for U-0.75Ti and U-2Mo, the two depleted uranium alloys most extensively produced for nonnuclear applications.

- **Unalloyed uranium** (as cast)
  Melting point: 1130 °C
  Density: 19 Mg/m^3
  Tensile strength: 450 MPa (65 ksi)
  Yield strength (0.2% offset): 207 MPa (30 ksi)
  Modulus of elasticity (tension): 172 GPa (25×10^6 psi)
  Elongation: 1 to 5%
  Reduction in area: 1 to 10%
  Hardness: 50 to 100 HRB

Hardness and strength of unalloyed uranium can be increased by warm or cold working.

- **Uranium alloys U-0.75Ti and U-2Mo**

	Melting point, °C	Density, Mg/m^3
U-0.75Ti	1200	18.6
U-2Mo	1150	18.5

Mechanical properties of these two alloys vary widely with heat treatment. The standard heat treatment for ordnance applications consists of heating into the gamma phase (about 850 °C), quenching in water or oil, and then aging at any of various temperatures in the range 350 to 450 °C. Strength increases and ductility decreases with increasing aging temperature until the material reaches a peak-aged condition at about 450 °C. Above this temperature, the material becomes overaged and loses strength but gains in ductility. Typical tensile data are given in Tables 1 and 2 for underaged, peak aged and overaged material.

Table 1 Tensile properties of U-0.75% Ti (Ref 3)

Yield strength		Tensile strength		Elonga-
MPa	ksi	MPa	ksi	
Underaged				
700	101	1350	196	14
850	123	1450	210	13
1000	145	1525	221	7½
Peak aged				
1200	174	1650	239	2½
Overaged				
1000	145	1450	210	3
850	123	1300	188	4
700	101	1175	170	7

Table 2 Tensile properties of U-2% Mo (Ref 3)

Yield strength		Tensile strength		Elongation, %
MPa	ksi	MPa	ksi	
Underaged				
700	101	1150	167	4
850	123	1200	174	4
1000	145	1250	181	2½
1150	167	1350	196	1½
Peak aged				
1350	196	1600	232	1½
Overaged				
1150	167	1375	199	1½
1000	145	1400	203	3½
850	123	1225	178	8
700	101	1125	163	17
550	80	925	134	24

Table 3 Estimated availability of depleted uranium (a)

	'78	'79	'80	'81	'82	'83	'84	'85	'86	'87	'88
UF_6	184.8	202.1	213.0	228.5	250.8	273.2	297.8	324.5	351.1	377.8	405.3
UF_4	67.7	63.5	50.2	45.7	44.6	37.4	35.0	32.5	27.9	27.9	27.9
Total....	252.5	265.6	263.2	274.2	295.4	310.6	332.8	357.0	379.0	405.7	433.2

(a) Metric tons (Mg) of metal. Data from U.S. Department of Energy (Feb 1979).

Production and Availability

Natural uranium (NU) contains about 0.7% of the fissionable isotope U-235, the remainder being comprised almost entirely of the isotope U-238. Power reactors of the type built in the United States require a U-235 content of 3%. Uranium is enriched from 0.7 to 3% U-235 by the gaseous diffusion process, in which the uranium is present as uranium hexafluoride (UF_6). Five to six kilograms of depleted uranium containing 0.2 to 0.3% U-235 are produced for each kilogram of uranium that is enriched to 3% U-235.

Depleted uranium (DU) is available mainly from government sources in the form of uranium hexafluoride (UF_6) or uranium tetrafluoride (UF_4); UF_4 also is known as "green salt." The amounts of depleted uranium estimated to be available for non-nuclear uses in 1978 through 1988 are shown in Table 3.

Green salt (UF_4) is obtained by chemically reducing UF_6 with hydrogen. Green salt is reduced to metal by an exothermic reaction with magnesium in a closed vessel. The product of this reaction is high-purity unalloyed uranium in the shape of a short cylinder, known as a "derby", weighing between 150 and 500 kg. Figure 2 shows schematically the steps involved in producing depleted uranium metal from the ore. At present there are five industrial producers of depleted uranium products for non-nuclear use in the United States and one in Canada.

Methods of Fabrication

The starting material for all depleted uranium products is derby metal. The usual methods of fabrication of DU products include casting, extrusion, rolling, and forging and swaging; these methods are discussed below. Almost all other conventional metalworking processes (including drawing, spinning, tube drawing, die forging and roll straightening) have been applied to DU, but few are of commercial significance.

Melting and Casting. Uranium can be melted by any of several different techniques. However, because uranium is very reactive when heated in air, melting must be done either under a protective inert atmosphere or in vacuum. Also, because uranium reacts with most ordinary crucible materials, it must be melted in a graphite crucible.

Uranium for industrial non-nuclear uses is melted in cold-wall vacuum induction furnaces (Ref 4). Crucibles and molds are made of high-density graphite. To prevent the uranium from contamination by carbon picked up quenching produce material which will not respond to aging; faster rates lead to formation of centerline voids.

Depending on property requirements and size of end product, solution treating is carried out in vacuum furnaces with internal or external water or oil quenching systems or in atmosphere furnaces or salt baths with external oil or water quenching. Control of hydrogen in the uranium during solution treating is vital for applications that require high ductility.

Aging of solution treated and quenched U-0.75Ti and U-2Mo alloys starts at about 350 °C and peaks at about 450 °C. Overaging and softening occur at higher temperatures. Aging is carried out in vacuum furnaces, inert-atmosphere furnaces or lead-tin baths. Aging times are usually 2 to 16 h, depending on property requirements. Typical aging curves for the two alloys are shown in Fig. 3 and 4.

Machining

Depleted uranium and its alloys are considered difficult to machine; nevertheless, depleted uranium is machined on a large scale at very high rates of production. The problems associated with machining are due to a combination of characteristics, including toughness and stringiness, abrasiveness, galling, work hardening, pyrophoricity, low modulus, high density, reactivity with coolants, reactivity with tools and grinding wheels, and toxicity. Some of these characteristics vary with alloy composition and heat treatment.

Health and safety considerations override all other problems because of uranium's high toxicity and pyrophoricity (see sections on health hazards and pyrophoricity, below). Uranium is heavy, and therefore it does not become airborne unless finely divided. Almost all machining of uranium results in some sparking or burning. Fine chips or finely divided oxides can become airborne, and each machine should be enclosed and heavily ventilated.

It is also important to prevent any metal that falls on the shop floor from being tracked throughout the plant. In general, protective footgear and clothing are used in the machining area.

Machining of uranium requires equipment having extra rigidity and ruggedness. Machine tools for uranium should have 50 to 100% greater capacity than tools for machining similar parts from steel.

Fig. 3 Aging behavior of U-0.75Ti (Ref 3)

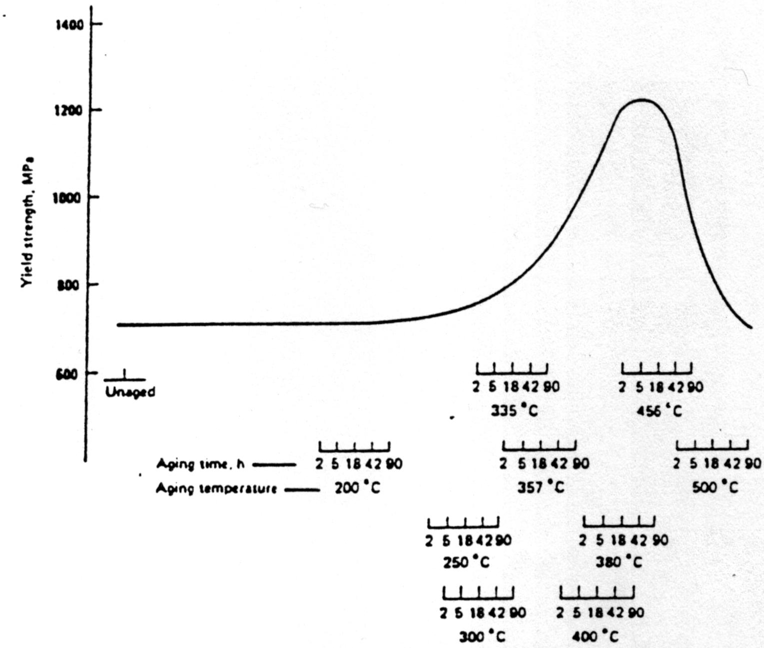
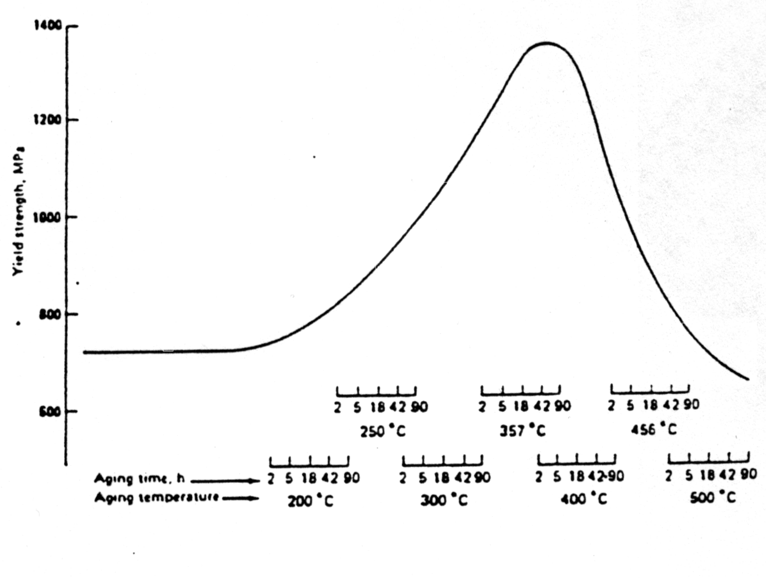


Fig. 4 Aging behavior of U-2Mo (Ref 3)



Turning. Uranium is turned on both conventional and numerically controlled heavy-duty equipment. In large-scale production, surface speeds up to 1.5 m/s are used for roughing, and speeds up to 3.0 m/s are used in finishing. A C-2 general-purpose grade of carbide performs satisfactorily for most turning operations; coated carbides normally used for machining steel perform well for most finishing operations.

Cutting tools having a positive rake angle are more free-cutting than negative-rake tools and put the least pressure on the workpiece. Accumulation of large quantities of chips should be avoided to diminish the potential for a pyrophoric reaction to occur.

Drilling and Tapping. Oil-hole drills, in combination with heavy flow of soluble-oil coolant, are favored for drilling uranium. Drills made of tool steels with high cobalt contents perform better than drills made of standard high speed tool steels. Drills must be kept sharp, and positive feeds must be used.

Uranium is difficult to tap. Body drills larger than those recommended for other materials are used to facilitate tapping. A tap generally can be used only once before it is reground. It is difficult to achieve thread depths greater than 50%.

Grinding. A series of tests was performed to determine optimum conditions for centerless plunge grinding of U-0.75Ti at hardness levels of 42 to 46 HRC (Ref 10). Best performance (best grinding ratio) was obtained with an A-80K-12 wheel (aluminum oxide with a vitrified binder), a 20% solution of soluble oil with chlorine and sulfur additions, an infeed rate of 0.27 mm/s, a grinding-wheel surface speed of 29.8 m/s and a regulating-wheel speed of 33.5 mm/s. Optimum operational settings will be slightly different for other uranium alloys and other types of grinding. Wheel wear, although greater than for most other metals, is considered acceptable for production grinding.

The most important consideration in grinding uranium is disposal of the fine grinding dust, which will react with the coolant and thus should not be allowed to accumulate in the machine.

Special Problems and Precautions

Depleted uranium requires special precautions during fabrication and sometimes during use. Ownership, production and use of depleted uranium are subject to state and federal regulations. These regulations are concerned mainly with three properties of the metal: radioactivity, toxicity and pyrophoricity. These problems can be handled routinely and have not constituted serious barriers to manufacture and use of depleted uranium products for commercial applications.

Health Hazards. Depleted uranium is only mildly radioactive (specific activity of 3.6×10^{-7} Ci/g vs 6.77×10^{-7} Ci/g for natural uranium) and is listed with natural uranium and thorium as a "low specific activity" (LSA) material in shipping regulations. Like lead and like metals with atomic numbers higher than lead, depleted uranium is a heavy-metal poison that can be lethal if a sufficient amount of dust or fumes is ingested.

The main hazard to health occurs in those fabrication steps where finely divided particles (dust or oxides) can become airborne. In operations such as melting and casting, machining, grinding, pickling, and heating without using a protective atmosphere or vacuum, it is essential to provide extensive ventilation and to monitor workers' breathing zones. Vents and fume hoods that protect workers are exhausted through carefully monitored filter systems. Workers must change footwear and clothing when leaving areas where finely divided uranium is present.

Users of depleted uranium objects generally do not have to be concerned with the health hazards presented by the metal. Solid pieces of depleted uranium are not sufficiently radioactive to be hazardous; neither do they present the kind of toxic hazard associated with finely divided dust or fumes.

Pyrophoricity. Large pieces of uranium will oxidize rapidly and will sustain slow combustion when heated in air to temperatures about 500 °C. The metal becomes truly pyrophoric only when finely divided. Because pyrophoric reactions take place at the surface of the metal, surface condition and the amount of exposed surface area are critical. Solid metal, particularly with a smoothly machined surface, reacts slowly; within several days the silvery as-machined surface turns to a tea color, and within a month turns black. Machine turnings, particularly fine turnings having literally hundreds of square metres of surface area per kilogram, may react sufficiently to generate enough heat to cause ignition if they are not kept cool under water. Grinding sludge, with still larger surface area, may react even under copious quantities of water.

Finely divided scrap is kept inert by storing it under water or mineral oil. Scrap prepared for shipment to disposal sites may be mixed with an inert insulating material such as sand, or may be mixed into concrete to ensure that no reaction occurs during transport.

Fires are extinguished by cooling the uranium and by restricting access of oxygen to the uranium by covering it with graphite powder or with a dry powdered chemical extinguisher. Water should never be used on uranium fires, because water reacts with the hot metal and generates hydrogen, which adds to the combustion.

Corrosion. The reactivity of uranium promotes corrosion, especially in severe environments. Figure 5 shows corrosion rates of unalloyed uranium and two uranium alloys in high-humidity, high-temperature air (Ref 11). Under such severe conditions, unalloyed depleted uranium corrodes rapidly, U-2Mo corrodes at about one-half the rate of unalloyed uranium and U-0.75Ti corrodes at a much slower rate.

Under normal storage conditions, uranium and uranium alloys have shelf lives of many years. Uranium and its alloys are shiny as machined, but in the presence of oxygen will acquire a dark oxide film in a few hours or a few days. This film serves as a protective coating.

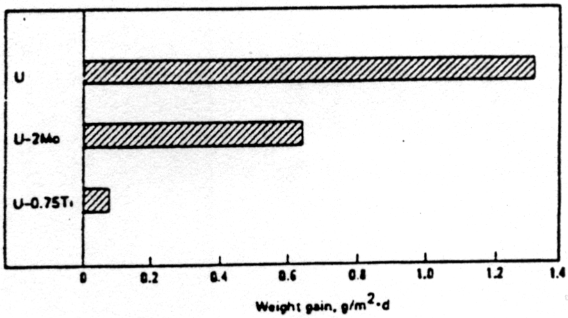
Corrosion protection for most unalloyed uranium objects (such as radiation shields) is obtained by painting with epoxy paints or by plating. A typical plating system consists of a copper flash, followed by nickel and finally cadmium.

Because uranium alloys corrode more slowly than unalloyed uranium, they generally do not require painting or plating. For example, U-0.75Ti and U-2Mo kinetic penetrators employed by the three military services are used without protective coatings, yet have projected storage lives of more than ten years and have passed all military atmospheric exposure tests.

Considerable data are available on corrosion of uranium and its alloys in water, steam and liquid metals (Ref 12).

Scrap Disposal and Transportation. Depleted uranium scrap is buried

Fig. 5 Average corrosion rates of unalloyed uranium and uranium alloys in hot, humid air



Specimens were tested at 74 °C and 75% relative humidity. Uranium alloys were tested in the solution treated and aged condition.

at designated licensed disposal sites in various parts of the United States. Methods of packaging scrap for transportation to disposal sites are determined mainly by government regulations. A typical method of packaging consists of placing the scrap in a 30-gallon drum and placing this drum inside a 55-gallon drum. Large pieces of scrap are simply placed within the inner drum. Chips are mixed with vermiculite or sand and placed in the inner drum. Very fine particulate material, especially grinding sludge, is mixed into concrete and placed in the drum in the form of concrete blocks.

Shipment of low specific activity (LSA) materials in interstate commerce is regulated by Title 49 of the Department of Transportation, which prescribes labeling and packaging. For depleted uranium the main consideration is that boxes and other containers be able to withstand a prescribed amount of mechanical shock and exposure to fire without releasing the uranium.

Licensing. Possession of more than 6.8 kg (15 lb) of depleted uranium in any form requires a license from the U. S. Nuclear Regulatory Commission. Title 10, Part 40, of Federal Regulations describes the requirements and the necessary steps for obtaining such a license. In addition, other local, state and federal regulations may apply to possession and use of uranium objects. Licenses are granted only to those who can satisfy requirements for technical competency, including the ability to control exposure of operating personnel, and to keep the concentration of particulate uranium in air and liquid effluents below statutory limits.

Certain users are excused from licensing requirements. If a DU product is used solely because of the high density of uranium, the user is excused from licensing requirements, and need only register with the U. S. Nuclear Regulatory Commission and dispose of the DU by returning it to a licensed recipient. (The user is *not* excused if he performs any metallurgical processing or mechanical working of the uranium.) If the DU is a counterweight or balance weight in an airplane, helicopter or missile, the user is totally excused from regulatory control. Users of DU-shielded shipping or storage containers or of DU-shielded equipment for cancer therapy or industrial radiography also are totally excused from regulatory control.

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