

OPTIONS FOR DISPOSAL AND REAPPLICATION OF DEPLETED URANIUM HEXAFLUORIDE

Stanley A. Fitch, CHP, RRPT
Trinitek Services, Inc.
PO Box 1608, Sandia Park, NM 87047-1608

ABSTRACT

The nuclear renaissance has spurred the need to enrich uranium to fuel power reactors to meet the nation's energy requirements. However, enriching uranium produces the volatile byproduct of DUF₆ tails. In an ambient environment, DUF₆ decomposes into uranium oxides and hydrogen fluoride (HF). This HF component makes DUF₆ unsuitable for disposal as low-level waste. To make DUF₆ suitable for disposal, it must be stabilized in a controlled process by converting it into uranium oxides and fluorine compounds by the processes of deconversion and fluorine extraction. Once stabilized, the DU and fluorine have reapplication potential that would delay or divert the need for disposal. Certain challenges confound this process, notably the chemical toxicity from elemental fluorine and DU, radiation hazards, limited low-level waste disposal capacity, and potential political and public opposition.

INTRODUCTION

In July 2005, the United States Congress passed the Energy Policy Act with the purpose, in part, of promoting the growth of the nuclear power. This action has since spurred a nuclear renaissance, with the submission of (as of the date of this paper) 15 reactor applications to the United States Nuclear Regulatory Commission (NRC). The renaissance is significantly increasing the demand for enriched uranium to fuel new and existing reactors. A byproduct of enriched uranium is depleted uranium hexafluoride (DUF₆), a volatile compound that NRC has determined is not suitable for disposal as low-level waste. DUF₆ must be stabilized for disposal, which means converting DUF₆ into uranium oxides. However, deconversion can cause significant health hazards from the production of elemental fluorine. Fluorine, the most reactive chemical element, reacts readily with hydrogen to form extremely hazardous hydrofluoric acid (HF_{aq}).

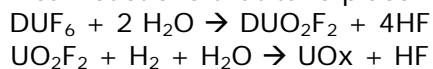
Approximately 90% of the uranium feed at an enrichment facility emerges as DUF₆ tails. Second only to uranium mining and milling, DUF₆ tails produces the largest waste stream of the entire nuclear fuel cycle. The United States Enrichment Corporation (USEC), Urenco Limited, AREVA, and General Electric have all either announced plans to build, or are building, new nuclear fuel enrichment facilities in the United States. According to International Isotopes, Inc., a leader in radioisotope production, if and when these facilities are completed, at their initial stated capacity, they will produce approximately 60 million pounds of DUF₆ tails each year. As is examined in this paper, numerous cross-cutting political and statutory factors drive the need for deconversion, and disposal or reapplication of the vast volume of DUF₆.

SCOPE OF THIS PAPER

This paper is an examination of the deconversion processes, reapplication and disposal options of the Uranium-238 oxides (²³⁸U₃O₈ and ²³⁸UO₂) and fluorine derived from these processes, and the resulting radiological and chemical hazards.

HOW DUF₆ DECONVERSION WORKS

The deconversion process starts with receiving the DUF₆ in solid form contained in a uranium byproduct cylinder (UBC). UBCs are placed into autoclaves and heated to vaporize and transfer the DUF₆ from the cylinder into a conversion reactor. The DUF₆ is then reacted with steam and hydrogen, which results in the formation of a uranium oxide and aqueous hydrogen fluoride. Safety controls in the process include scrubbers, filters, and monitoring equipment to assure proper deconversion and to prevent airborne releases. The chemical equations below show the chemical reactions that take place in the process.



The two products of the conversion are uranium oxide and hydrogen fluoride gas. Uranium oxide is more chemically stable than DUF₆, making it suitable for disposal in a authorized low-level waste facility, or for storage or reuse. The fluorine produced by deconversion can be used to manufacture hydrofluoric acid (HF_{aq}) or for reapplication in the form of stable fluoridated compounds.

HEALTH CONCERNS

The intake of DUF₆ poses chemical hazards from the toxicity of F₂ and DU, and radiological hazards from the DU. This section evaluates these hazards, which would be present at a facility either de-converting DUF₆ or otherwise chemically altering the compound to reuse (reapply) its constituents.

Volatility of Uranium Hexafluoride

Atomic fluorine is the most chemically reactive and electronegative of all the elements, in part because of the weakness of the F–F bond (binding energy = 153 kJ/mol), but mostly because it is such a powerful oxidizing agent. Fluorine combines with every element in the period table except helium, neon, and argon. With a few metals, it forms a surface film of metal fluoride, which adheres tightly enough to prevent further reaction. This is the case with nickel, where the product is NiF₂. Fluorine gas is ordinarily stored in containers made of a nickel alloy, such as stainless steel (an iron-chromium-nickel alloy) or Monel (a nickel-copper alloy). Fluorine also reacts with many compounds including water. This means that reactions of fluorine with other species cannot be carried out in water solution. [1]

When isolated in elemental form, fluorine appears as a poisonous, pale, yellowish brown gas, with chemical formula F₂. Like other halogens, molecular fluorine is highly dangerous; it causes severe chemical burns on contact with skin.

It is interesting to note that despite its reactivity, fluorine bound in the form of fluorides (fluorine-metal compounds) are among the most stable of salts. One such salt is uranium tetrafluoride (UF₄), commonly referred to as "green salt."

Fluorine reacts explosively with hydrogen, even at -253°C, the boiling point of hydrogen where the fluorine is in solid form. It is an exothermic reaction. It is so reactive that metals, and even water, as well as other substances (including asbestos), burn with a bright flame in a jet of fluorine gas. Fluorine is far too reactive to be found in elemental form.

The hydrogen-fluorine reaction forms hydrogen fluoride (HF) gas. Aqueous solutions of HF, called hydrofluoric acid (HF_{aq}), are strongly corrosive. HF is highly soluble in water. In moist air, hydrogen fluoride reacts with water vapors to form dangerous HF_{aq} fumes.

Inhaled and absorbed into the human body, the same reaction occurs, forming HF_{aq} at the pulmonary, vascular, and cellular levels. The ACGIH threshold limit value (TLV) is 3 ppm (parts per million). [2] In sufficient quantities, exposure results in death within a few hours.

Uranium hexafluoride (UF_6) spontaneously decomposes into UF_4 and F_2 . (This was first noted during the Manhattan Project. [3])[†] A significant release of UF_6 could result in significant health consequences or death to workers and members of the public. During the generation, storage, and deconversion of DUF_6 , the potential chemical hazard is far greater than the potential radiological hazard.

UF_4 reacts slowly with moisture at ambient temperature, forming uranium dioxide (UO_2) and HF_{aq} . Like all uranium salts, UF_4 is toxic if inhaled, ingested, or absorbed through skin contact. UF_4 is less stable than uranium oxides. Because UF_4 is toxic and because HF_{aq} is corrosive, it is thus less favorable for long-term disposal than the uranium oxides. Therefore, the United States Nuclear Regulatory Commission (NRC) has determined that DUF_4 is not suitable for near surface disposal as low-level waste (LLW) under 10CFR§ 61. The recommended option is to convert the DUF_4 to the significantly more stable forms of either U_3O_8 or UO_2 and dispose of the fluoride residues separately or to reuse them if a commercial option is available.

Chemical Hazards Due to Hydrofluoric Acid

HF_{aq} is a contact poison. Inhaled and absorbed into the human body, interaction of F_2 with water forms HF_{aq} at the pulmonary, vascular, and cellular levels. The OSHA and ACGIH threshold limit value (TLV) for airborne concentrations is 3 ppm (2.3 mg/m^3) [4] and the IDLH (immediately dangerous to life and health) value published by NIOSH is 20 ppm (46 mg/m^3). [5] In sufficient quantities, exposure results in death. Deichmann and Gerarde (1969) stated that 50 ppm may be fatal when inhaled for 30 to 60 minutes. [6] (In a particular instance, death occurred within 6.5 hours after an ingestion of 1.5 grams of HF_{aq} at an unknown concentration. [7])

HF_{aq} interacts with many metal oxides in the body, forming fluoride compounds (principally metallic). After intake to the body, HF_{aq} reacts primarily with the highly-prevalent and biologically important ions Ca^{2+} and Mg^{2+} . Sufficient uptakes can cause hypocalcemia (an abnormally low concentration of calcium in the blood) and hypomagnesemia (an abnormally low concentration of magnesium in the blood).

Because it is a weak acid, and hence has a low dissociation constant, HF_{aq} penetrates tissue more quickly than strong acids. Symptoms of exposure to hydrofluoric acid may not be immediately evident. HF_{aq} interferes with nerve function, so burns may not initially be painful. Accidental exposures can go unnoticed, delaying treatment and increasing the extent and seriousness of the injury. Death can occur if as little as 2.5% of total body surface area is exposed to concentrated HF_{aq} , while hypocalcemia and hypomagnesemia can occur from smaller surface area or lower concentrations. Thus, hydrofluoric acid exposure is often treated with calcium gluconate, providing a source of Ca^{2+} to sequester the fluoride ions. HF_{aq} chemical burns can be treated with a water wash and 2.5% calcium gluconate gel or special rinsing solutions. [8]

[†] Because F_2 is so reactive, scientists on the project were plagued with corrosion of the piping and other components that carried the UF_6 . The scientists developed the solution of coating process equipment with nickel metal or Teflon, which resist F_2 corrosion.

Radiological Hazards Due to Depleted Uranium

As noted above, UF_6 spontaneously decomposes into UF_4 and F_2 (the same is true for DUF_6). Assuming a release in ambient air, anhydrous DUF_4 would be made airborne and would be respirable to humans (and other animals). Because Uranium-238 is radioactive, it decays by the modes and energies indicated in Table 1:

Table 1 – Uranium-238 Decay Modes and Energies

Half-life = 4.468E+9 years

Mode	Energy (MeV)	Intensity
alpha	4198	79.0%
	4151	20.9%
	4038	0.078%
beta	-----	-----
gamma	0.04955	0.064%
	0.1135	0.0102%
spontaneous fission	-----	0.00005%

The total decay energy is 4.274 MeV.

Assuming that DUF_6 decomposed in air results in $DUF_4 + 2(HF)$ in spatial equilibrium, the following radiation doses are estimated according to the TLV and IDLH concentrations for HF:

Table 2 – Comparison of HF Hazard Levels to DUF_4 Radiation Dose

Category	HF conc.	HF conc. g/cm ³	DUF_4 conc. g/cm ³	DUF_4 conc. μCi/mL	Dose from DUF_4
TLV for HF	3 ppm	3.87×10^{-9}	3.04×10^{-8}	1.02×10^{-8}	1.3 rem/hr
IDLH for HF	20 ppm	2.58×10^{-8}	2.02×10^{-7}	6.80×10^{-8}	8.5 rem/hr
Death from HF	50 ppm-hr	6.45×10^{-8}	5.06×10^{-7}	1.70×10^{-7}	21.3 rem
1 DAC U-238 Class W	0.006 ppm	7.58×10^{-12}	5.95×10^{-11}	2×10^{-11}	0.0025 rem/hr

(Note: 1 rem = 0.01 sieverts)

Given:

Molar mass of DUF_4	314.0226 g/mol
Molar mass of HF	20.01 g/mol
Density of air	0.00129 g/cm ³
Ratio of DUF_4 to 2(HF) in air	~7.8466
1 DAC U-238 Class W [9]	2×10^{-11} μCi/mL
1 DAC-hour	0.0025 rem

It is interesting to note from the above that while the inhalation of 50 ppm of HF in 1 hour could hypothetically result in death, the corresponding acute radiation dose of 21.3 rem is not life-threatening. (For example, the LD-50[†] for radiation is approximately 400 rem acute dose.) This is not to say that exposures to DUF₆ need not be kept as low as reasonably achievable (ALARA).

Toxicity of Depleted Uranium

Depleted uranium is a heavy metal. Therefore it exhibits chemical toxicity in addition to radiological toxicity. The target organs for chemical toxicity from an uptake of DU are the kidneys. Whether ingested or inhaled, once in the bloodstream, uranium compounds are filtered by the kidneys, where they can cause damage to the kidney cells. At low acute intake levels (less than 4 milligrams), the kidney repairs itself over a period of several weeks after the uranium exposure has stopped. [10] Above about 4 milligrams acute intake, damage can be detected by the presence of protein and dead cells in the urine, but there are no other symptoms. Very high uranium intakes can cause acute kidney failure (>40 mg) and death (50% lethality at 230 mg).

Table 3 – Health Effects from Intake of Soluble Uranium [11]

Health Effects	Uranium per kg body weight (mg U/kg)	Uranium Uptake in a 70-kg Person (mg)	Uranium Intake by a 70-kg Person (mg)
50% Lethality	1.63	114	230
Threshold for Permanent Renal Damage	0.3	21	40
Threshold for Transient Renal Injury or Effect	0.058	4.06	8
No Effect	0.03	2.1	4

The uptake/intake ratio by absorption of soluble DU into the blood from respiration is approximately ½. Thus, it appears that a single inhalation (intake) of 4 mg of DU by an adult is not likely to produce any health effect. Because of DU chemical toxicity, NRC limits soluble uranium intake to the 10 milligrams/week for workers as specified in 10CFR§ 20.1201(e). This is equivalent to 0.143 mg/kg/week in a 70-kg person.

Table 4 – Comparison of HF Hazard Levels to DU Uptake

Category	HF conc.	DU conc.	DU conc. mg/cm ³	Uptake of Soluble DU	Radiation Dose
TLV for HF	3 ppm	18 ppm	2.30 x 10 ⁻⁵	13.8 mg/hr	1.3 rem/hr
IDLH for HF	20 ppm	119 ppm	1.54 x 10 ⁻⁴	92.1 mg/hr	8.5 rem/hr
Death from HF	50 ppm-hr	297 ppm-hr	2.84 x 10 ⁻⁴	230.2 mg/hr	21.3 rem/hr

(Note: 1 rem = 0.01 sieverts)

[†] "LD-50" refers to the radiation dose at which approximately 50% of exposed persons will die if they do not receive medical attention.

Given (in addition to Table 2):

The DU is in the form of DUF ₄	
Atomic mass of DU	~238.0415 g/mol
Ratio of DU to 2(HF) in air	~5.9481
Uptake/Intake retention ratio of soluble DU	~0.5

Table 4 compares fluorine toxicity levels to radiation dose and DU uptake. Here are some interesting analogies:

- At the 3 ppm Threshold Limit Value (TLV), NRC's chemical toxicity limit of 10 milligrams/week for soluble uranium would be reached in approximately 43.5 minutes.
- A one-hour exposure to DUF₆ at a concentration that would result in 50 ppm respirable HF concentration will deposit 230.2 mg of DU in the person. That number closely approximates the 50% lethality threshold (230 mg) for DU toxicity in a 70-kg person.
- The F₂ and DU chemical toxicity hazards are a far greater concern than the radiation hazards from DU.

Consequence Analysis

After the enrichment of uranium, DUF₆ tails are stored in steel cylinders in open-air yards close to the enrichment plant. Each cylinder is commonly referred to as "UBC", which is an acronym for "uranium byproduct cylinder." Hundreds of UBCs are commonly stored at enrichment plants. Each UBC contains up to 14 tons (1.3×10^{10} milligrams) of solid DUF₆. The estimated life time of the UBC is in excess of 40 years. Nevertheless, UBCs are subject to failure and are therefore required to be routinely inspected for signs of corrosion and leaks. [12] In the event of a catastrophic release from a ruptured (or otherwise breached) UBC, unprotected persons could inhale, ingest, and absorb lethal quantities of DUF₆. Two scenarios are examined herein using the ALOHA dispersal code. (ALOHA and CAMEO are EPA emergency response computer codes recommended for use by NRC in consequence analysis at uranium enrichment and DUF₆ deconversion facilities.)

Scenario One

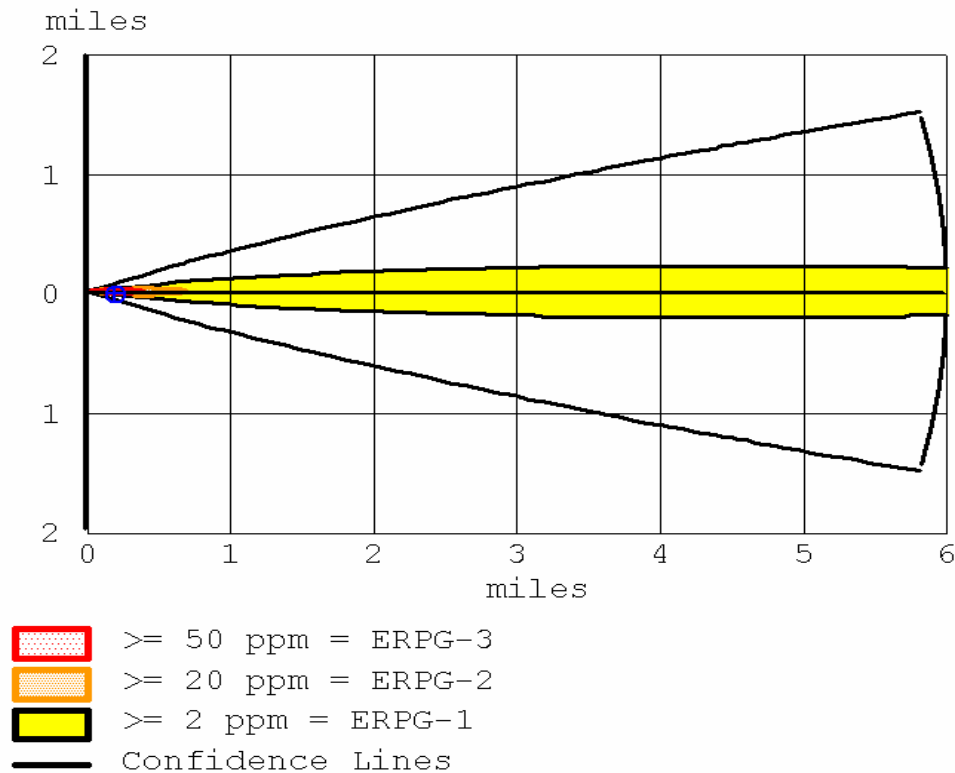
For the first scenario, the following assumptions are made:

- A UBC leaks its contents from a 2-inch leak in the containment. The mass of F₂ in the UBC is 0.89 tons (14 tons DUF₆).
- The location is Idaho Falls, Idaho.
- Atmospheric Data

Wind: 5 knots from SW at 3 meters height	
Ground Roughness: open country	Cloud Cover: 5 tenths
Air Temperature: 32° F	Stability Class: E
Inversion Height: 100 feet	Relative Humidity: 50%

Scenario One assumes an unlikely release of the entire contents of the UBC in a short period of time without any safeguards.[§] The dispersal pattern is depicted in Figure 1. Based on the plot, a person located downwind of the release could receive a lethal dose of HF. Scenario One assumes the worst case, that is a rapid release by a light wind in relatively stable air affected by an inversion. Based on the above ALOHA results, one could assume that UBC storage locations should not be located closer than 2 miles from a given populace.

[§] Note: The confidence levels of both Scenario One and Two are low because they focus primarily on total mass of F₂ available for release and that formation of HF is virtually instantaneous. The scenarios do not provide specificity of facility and UBC design and physical orientations at a hypothetical usage or storage facility.

Figure 1 – Scenario One, ALOHA Dispersal Plot of HF Gas**Scenario Two**

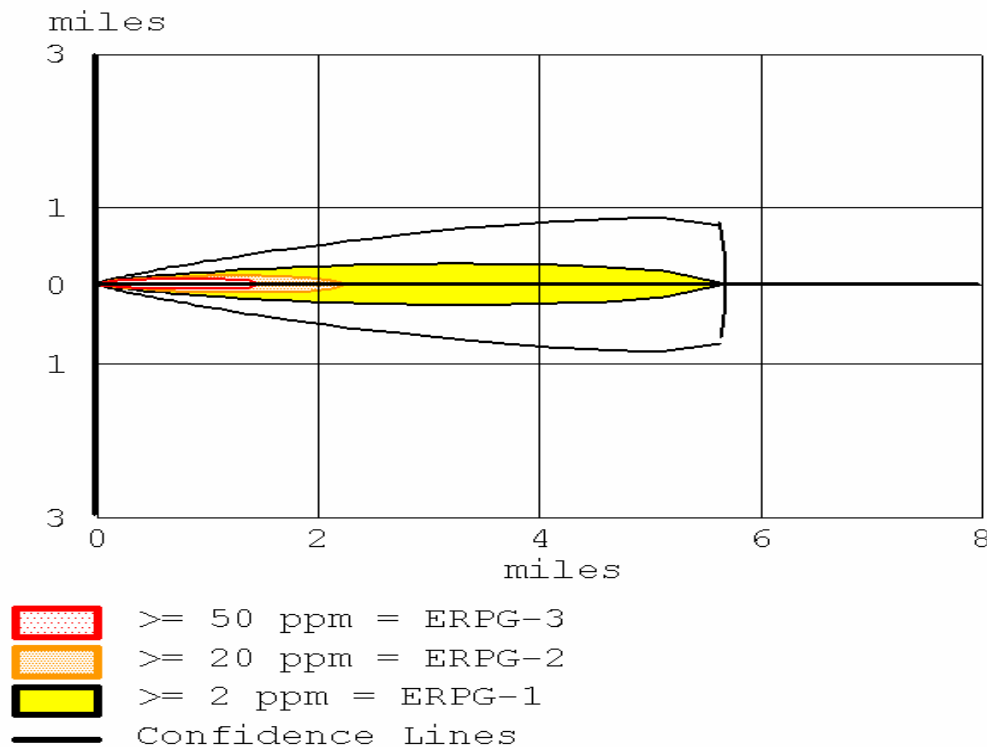
For the second scenario, the following assumptions are made:

- A UBC leaks its contents from a 2-inch leak in the containment. The mass of F_2 in the UBC is 0.89 tons (14 tons DUF_6).
- The location is Idaho Falls, Idaho.
- Atmospheric Data

Wind: 25 knots from W at 3 meters height	Cloud Cover: zero
Ground Roughness: open country	Stability Class: D
Air Temperature: 90° F	Relative Humidity: 5%
Inversion Height: unlimited	

The dispersal pattern is depicted in Figure 2.

As expected, Scenario Two shows much more rapid dispersal of the HF due to significant instability. However, regardless of the particular scenario, emergency notification and evacuation plans would be necessary for workers and the public situated to such a facility. That point is of significant concern to environmental agencies and citizens groups, who frequently contend that quantities of DUF_6 in storage should be greatly limited. A number of citizens groups further contend that this is a further indication that fuel processing for nuclear power is simply too unsafe to permit the practice.

Figure 2 – Scenario Two, ALOHA Dispersal Plot of HF Gas

LOW-LEVEL WASTE DISPOSAL

The NRC has determined that DU is a low-level waste (LLW). Viable, licensed LLW repositories in the United States include the *EnergySolutions* facility at Clive, Utah and the Nevada Test Site (NTS) LLW disposal facility operated by the Department of Energy. Uranium mill tailings impoundments are being considered.

Another location is the U.S. Ecology facility near Richland, Washington. The facility is available on to LLW generated in the Northwest and Rocky Mountain LLW Compacts. The activity allowance remaining for disposal of DU at Richland is only 13 curies (approximately 26,000 kg) as limited by the State of Washington because uranium is relatively mobile in the Hanford-area soils. [13] This limit excludes Richland from practical consideration because the proposed private-sector deconversion facilities will be capable of producing 7 million kilograms (3,500 curies/year) of DU per year for disposal.

The Clive facility owned by *EnergySolutions* and licensed by the Utah Division of Radiation Control (UDRC) has a practical limit in the amount of all radioactive waste (including DU) that it can dispose. That limit is currently 20,000 curies. [14] The Clive facility could, for a limited period of time, accept the 3,500 curies/year likely to be generated by one of the proposed private-sector deconversion facilities. Eventually, to handle the large amount of DU to be generated by the nuclear renaissance, disposal capacity at the Clive facility would need to be increased pursuant to authorization by the UDRC.

DOE is considering adding capacity to NTS to handle its own DU waste in addition to that of

industry.[15] To wit, DOE is considering the appropriate disposal facility at NTS (i.e., Area 3 or Area 5) and the evaluation of the capacity for the selected disposal facility. According to DOE, they intend to develop disposal cells at Yucca Flat in five craters formed from the underground testing of nuclear weapons. Area 3 at NTS has a developed area of 20 acres. A disposal facility was constructed in Area 5 (Frenchman's Flat) adjacent to the testing area used for atmospheric tests of nuclear weapons. The active area in Area 5 occupies 92 acres. An additional 640 acres within Area 5 is slated for development. According to DOE, each disposal area has an enormous potential capacity that could be made available for the disposal of waste by developing the NTS disposal sites.

The development of additional capacity at NTS would constitute a significant NEPA (National Environmental Policy Act) action affecting the environment. Consequently, NEPA documentation would be required that would necessarily involve all concerned stakeholders (e.g., State of Nevada). According to DOE, an environmental impact statement (EIS) would likely be required.

Table 5 – Summary of Disposal Options for DU

Location	Mitigating Factors
Uranium Mill Tailings Impoundments 11e.(2) alternate feed	GEIS required from NRC; questions remain as to whether a 10CFR§ 61 license may be required in addition to a 10CFR§ 40 license.
Abandoned Uranium Mines	Poor technical feasibility; each mine must meet the licensing and performance requirements of 10CFR§ 61; political and public opposition.
Temporary Onsite Storage at Uranium Enrichment Plants	Public and political opposition; equipment maintenance; potential for environmental releases of HF.
US Ecology Richland, Washington	Limited storage capacity due to waste mobility in soil; accepts waste only from the Northwest and Rocky Mountain Compacts.
Energy Solutions Clive, Utah	Disposal capacity and license limits would need to be increased to meet the expected demand.
Nevada Test Site	DOE would need to increase disposal capacity to meet the expected demand; resistance from the State of Nevada; would require extensive NEPA analyses.

POLITICAL, PUBLIC, AND INDUSTRIAL PERSPECTIVES

As noted previously, UF_6 spontaneously decomposes into UF_4 and F_2 . Also noted previously,

generation and storage of DUF_6 can lead to catastrophic results. A significant release of UF_6 could result in significant health consequences or death to workers and members of the public from the dissociation to UF_4 and F_2 and the immediate formation of HF_{aq} in the body. (As evaluated above, the F_2 and DU chemical toxicity hazards are a far greater concern than the radiation dose from the DU.) However, disposal capacity at the current LLW facilities is limited.

The need for stabilization and the nation's limited disposal capacity was a major concern in licensing the National Enrichment Facility (NEF) in Lea County, New Mexico, and the corresponding generation of tons of DUF_6 . The NEF is currently being built by Urenco on a site five miles east of the small town of Eunice. According to Urenco [16], this site was selected for the NEF for several reasons, notably New Mexico's history as a hub of scientific research and development and strong support from county leaders, business people, and state officials.

Urenco claims that the facility will enable the United States to have a domestic source of enriched uranium for the country's commercial nuclear power plants. Urenco further claims that the NEF will use the world's most advanced, energy-efficient and cost effective uranium enrichment technology. This claim was no doubt made to allay the concerns of the public.

Because NEF will generate such large quantities of waste, and because Urenco proposes long-term storage of the material pending a disposal pathway, the public and the New Mexico Environment Department expressed the concern that without an established pathway, the hundreds of DUF_6 cylinders could become legacy waste or, worse yet, result in a huge release of F_2 or HF to the environment. This concern will likely be solved in the near term by private-sector investors.

Urenco notes that the NEF will provide a sustainable domestic supply of low enriched uranium (LEU), thereby substantially reducing American reliance on the global nuclear fuel marketplace and encouraging competition within the United States market. USEC is the only other company currently producing enriched uranium in the US.

Full capacity operation of the NEF is expected to annually produce 5.9 million separative work units (SWUs) of uranium, which is approximately one-fourth of current enrichment services demand in the United States. The NEF will store its DU tails in UBCs at the NEF site. Responding to cooperative arrangement between Urenco and the New Mexico Environment Department, the NRC limited the maximum retention time to 18 years for individual UBCs. According to Urenco, the projected life of each UBC is greater than 40 years if properly maintained.

While the Nuclear Information and Resource Service (NIRS) and Public Citizen (PC) strongly opposed licensing and construction of the NEF [17], the majority people in Lea County have favorably received the facility in the hopes of creating jobs and stabilizing their economy, which has been primarily driven by ranching and the oil and gas industry.

POSSIBLE SOLUTIONS FOR REAPPLICATION OF DUF_6

A key challenge to the production DUF_6 is to determine suitable uses for the DU aside from disposal. For a number of years scientists, industry, and government have explored possible reapplications of DU. Some of those possibilities are discussed below.

DOE DUF_6 Use Roadmap

On July 6, 1999, DOE issued a final plan as required by Public Law 105-204 for the national deconversion and reapplication of DUF_6 . In that final plan, DOE developed a DUF_6 Materials Use Roadmap to establish a plan for the reapplication of DUF_6 and DUF_6 -derived materials for uses in both the Federal private sector. In June 2000, DOE published the Roadmap and identified a number of viable uses for DU [18]:

Nuclear Fuel Cycle

DOE identified that in nuclear fuel cycle applications, DU can be used as:

- feed for further enrichment;
- a fertile material to create plutonium for nuclear fuel in fast breeder reactors;
- a diluent to down-blend highly enriched uranium to reactor-grade fuel (mixed oxide fuel or "MOX" discussed below); or
- potentially as a component of a waste repository structural components.

Radiation Shielding

A market for DU exists in radiation shielding from x-rays or gamma rays. DOE cited the method of using DU compounds as a component in concrete aggregate. DU compounds in concrete achieve the same shielding performance as that achieved by standard concrete of twice the thickness.

Military Applications

Continued use in conventional military applications such as tank armor and armor piercing projectiles.

Commercial Applications

- Continued use for counterweights in a variety of applications, primarily the aerospace industry;
- DU catalysts;
- A source of fluorine to manufacture a large variety of industrial chemicals.

Reapplication of DU in Mixed Oxide Fuel (MOX) [19]

At the end of the Cold War, the United States and the former Soviet Union began dismantling nuclear weapons, which left both countries with large stocks of surplus weapons-grade highly enriched uranium and plutonium. In September 2000, the United States and Russia signed an agreement to reduce their respective stockpiles of surplus plutonium. The DOE, in conjunction with industry is developing programs to use depleted uranium dioxide (DUO_2) as a diluent to down-blend 34 metric tons of surplus weapons-grade plutonium into mixed oxide (MOX) fuel to be used in commercial nuclear power plants.

MOX is a blend of plutonium dioxide (PuO_2) and DUO_2 . The process of converting the fissile material into MOX fuel renders the plutonium less attractive for use in nuclear weapons. In some countries, MOX fuel is manufactured by recycling plutonium from spent nuclear fuel. That is not the case in the proposed MOX program in the U.S.

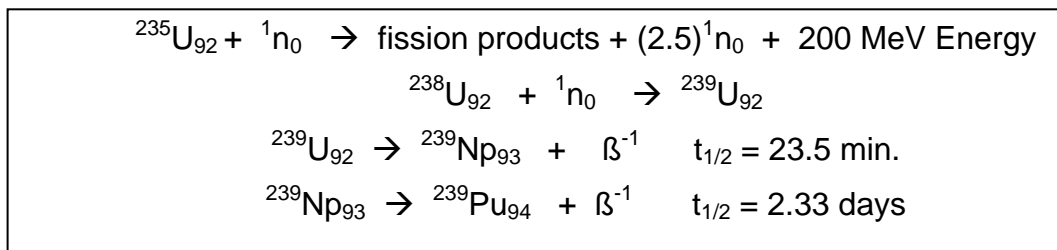
MOX production and use is not new. Fast breeder reactors (FBRs) usually use a MOX core of up to 20% Plutonium-239 dioxide ($^{239}\text{PuO}_2$) and at least 80% Uranium-238 dioxide ($^{238}\text{UO}_2$). European countries such as the United Kingdom, Germany, Belgium, and France

have been fabricating MOX fuel and using the material in commercial reactors for many years. MOX fuel was fabricated and used in several commercial reactors in the United States in the 1970s as part of a development program.

Using the plutonium as MOX reactor fuel makes reusing it for any other purposes difficult. Therefore, spent MOX fuel will not be reprocessed for subsequent reuse. Instead, the spent MOX fuel will be disposed of as high-level waste in a geologic repository.

Reapplication of DU for Plutonium Production

Plutonium-239 is produced from the interaction of Uranium-238 with neutrons released by fission of Uranium-235:



Each U-235 that undergoes fission produces an average of 2.5 neutrons. In contrast, some U-238 nuclei capture neutrons, become U-239, and subsequently emit two beta particles to produce Pu-239. Pu-239 itself is fissionable material, and therefore attractive for producing power in nuclear reactors. The production of Pu-239 is also an attractive alternative to the burn-up of U-235 in power reactors. Ergo, breeder reactors were developed.

A breeder reactor [20] is a nuclear reactor that generates new fissile material (Pu-239 for the sake of this discussion) at a greater rate than it consumes the initial fissile stock. These reactors exhibit superior fuel economy; a normal reactor can consume less than 1% of the natural uranium that begins the fuel cycle, whereas a breeder can utilize a much greater percentage of the initial fissionable material. There is also a dramatic reduction in the volume of waste produced by breeder reactors.

Breeder reactors produce additional fissile material by neutron irradiation of "fertile material," particularly Uranium-238 and Thorium-232. The DU produced by DUF₆ deconversion would make an ideal source of U-238 for use as fertile material. In a breeder reactor, fertile materials are placed in the fuel and in a "breeder blanket" surrounding the reactor core. The fertile material is bombarded by fission neutrons, creating new fissile material as an activation product. Production of fissile material takes place to some extent in the fuel of all current commercial nuclear power reactors. For example, towards the end of its life, a uranium pressurized water reactor (PWR) fuel element is producing more power from the fissioning of Pu-239 than from the remaining U-235.

Extraction of Fluorine for Industrial Reapplication

With the nuclear renaissance, a handful of private companies have decided to pursue processes to extract fluorine from DUF₆ tails. The processes are intended to produce high-value specialty fluoride gases for use in the fabrication of microelectronics and in other applications.

One company that intends to extract fluorine for reapplication is International Isotopes, Inc.

(INIS). On June 4, 2008, INIS issued press releases announcing its intentions to construct a commercial facility to process DUF_6 tails from commercial uranium enrichment operations. According to INIS, the facility will employ a two-step conversion process. The first step involves the conversion of UF_6 to UF_4 (referred to as "green salt"). The UF_4 will then be used as the raw material for the second step, which employs the fluorine extraction process patented by INIS (Patent 6,086,836). According to press releases issued by INIS, they expect that the facility will output significant volumes of high-purity, high-value fluoride gases.

INIS is advertising a complete solution to stabilization and disposition of DUF_6 tails. INIS claims that enrichment firms will be relieved of the costs of constructing their own deconversion facilities, management and storage costs of UBCs, cost of stabilizing DUF_6 , and much of the transportation requirements as well. INIS contends that the deconversion facility will provide a more acceptable, "green" solution for the environment, communities, and governments.

SUMMARY

The nuclear renaissance has spurred the need to enrich uranium to fuel power reactors to meet the nation's energy requirements. However, enriching uranium produces the volatile byproduct of DUF_6 tails. In an ambient environment, DUF_6 decomposes into uranium oxides and hydrogen fluoride (HF). This HF component makes DUF_6 unsuitable for disposal as low-level waste. To make DUF_6 suitable for disposal, it must be stabilized in a controlled process by converting it into uranium oxides and fluorine compounds by the processes of deconversion and fluorine extraction. Once stabilized, the DU and fluorine have reapplication potential that would delay or divert the need for disposal. Certain challenges confound this process, notably the chemical toxicity from elemental fluorine and DU, radiation hazards, limited low-level waste disposal capacity, and potential political and public opposition.

ACRONYMS

ACGIH	American Congress of Governmental Industrial Hygienists
ALOHA	Areal Locations of Hazardous Atmospheres [computer code]
cm ³	cubic centimeter
DOE	United States Department of Energy
DU	depleted uranium
DUF ₄	depleted uranium tetrafluoride ("green salt")
DUF ₆	depleted uranium hexafluoride
DUO ₂	depleted uranium dioxide
EPA	United States Environmental Protection Agency
ERPG	Emergency Response Protective [Action] Guide level
F ₂	elemental fluorine
FEP	Fluorine Extraction Process
GEIS	Generic Environmental Impact Statement
HF	hydrogen fluoride (anhydrous)
HF _{aq}	hydrofluoric acid
hr	hour
IDLH	Immediately Dangerous to Life and Health
INIS	International Isotopes, Inc.
kg	kilogram
LLW	Low-Level Waste (as defined by 10CFR§ 61)
MeV	million electron volts
mg	milligram
mL	milliliter
MOX	mixed oxide fuel
NEPA	National Environmental Policy Act
NIOSH	National Institute for Occupational Safety and Health
NRC	United States Nuclear Regulatory Commission
NTS	Nevada Test Site
ppm	parts per million
TLV	Threshold Limit Value
UBC	uranium byproduct cylinder
UO ₂	uranium dioxide

REFERENCES

1. William L. Masterton, Cecile N. Hurley, Chemistry Principles & Reactions, Third Edition, 1997, Saunders College Publishing, ISBN: 0-03-005889-9.
2. American Congress of Governmental Industrial Hygienists. TLVs and BEIs, Guide to Exposure Limit Values; 2008 Edition.
3. Wikipedia Foundation, Inc. Fluorine. Available at: <http://en.wikipedia.org/wiki/Fluorine/>. First accessed on 7/21/2008.
4. American Congress of Governmental Industrial Hygienists. TLVs and BEIs, Guide to Exposure Limit Values; 2008 Edition.
5. National Institute for Occupational Health, Centers for Disease Control and Prevention. Hydrogen fluoride (as F) IDLH Documentation. Available at: <http://www.cdc.gov/niosh/idlh/7664393.html>. First accessed on 7/23/2008.
6. Ibid.
7. Environment, Health and Safety Program of University of North Carolina. Hydrofluoric Acid Chemical Safety Information. Available at: <http://ehs.unc.edu/environmental/docs/hydrofluoricacid.pdf>. First accessed on 7/21/2008.
8. Wikipedia Foundation, Inc. Hydrofluoric Acid. Available at: http://en.wikipedia.org/wiki/Hydrofluoric_acid/. First accessed on 7/21/2008.
9. Nuclear Regulatory Commission. Table 1 of Appendix B of 10CFR§ 20, "Standards for Radiation Protection."
10. Argonne National Laboratory. Uranium Health Effects. Available at: <http://web.ead.anl.gov/uranium/guide/ucompound/health/index.cfm>. First accessed on 7/26/2008.
11. Allen Brodsky, Sc.D., Review of Radiation Risks & Uranium Toxicity, January 1996, RSA Publications.
12. Nuclear Regulatory Commission. 10CFR§ 50 "Domestic Licensing of Production and Utilization Facilities.
13. Oak Ridge National Laboratory, ORNL/TM-2000/10 "Depleted Uranium Storage and Disposal Trade Study: Summary Report", February 2000. Available at: <http://www.osti.gov/bridge/servlets/purl/752983-MhasEM/webviewable/752983.pdf>.
14. Utah Radioactive Material License #2300249 Amendment #0, dated 1/25/2008, issued by the Division of Radiation Control, Utah Department of Environmental Quality.
15. Oak Ridge National Laboratory, ORNL/TM-2000/10 "Depleted Uranium Storage and Disposal Trade Study: Summary Report", February 2000. Available at: <http://www.osti.gov/bridge/servlets/purl/752983-MhasEM/webviewable/752983.pdf>.
16. Urenco Limited. The National Enrichment Facility. Available at: <http://www.urencolimited.com/sectionFrontPage.aspx?m=1705>. Website first accessed on 6/4/2008.
17. Nuclear Information and Resource Service. Louisiana Energy Services and Enrichment Plant. Available at <http://www.nirs.org/les/les.htm>. Website first accessed on 6/4/2008.
18. U.S. Department of Energy. Potential Uses of Depleted Uranium. Available at: <http://web.ead.anl.gov/uranium/uses/index.cfm>. Website first accessed on 7/23/2008.
19. A significant source of reference material for the MOX section was taken from the following NRC website: <http://www.nrc.gov/materials/fuel-cycle-fac/mox/licensing.html>
20. Samuel Glasstone, Walter H. Jordan, Nuclear Power and Its Environmental Effects, 1982, American Nuclear Society, La Grange Park, IL.

The following websites were accessed in the preparation of this paper and may serve as excellent references for the reader:

<http://www.atsdr.cdc.gov/HAC/pha/NuclearFuelServices/NuclearFuelServicesPHA052907.pdf>

http://www.atsdr.cdc.gov/HAC/PHA/oakridgely12/oak_p6.html

http://www.atsdr.cdc.gov/HAC/pha/paducah2/pgd_toc.html

http://www.atsdr.cdc.gov/HAC/pha/paducah2/pgd_p3.html

http://www.atsdr.cdc.gov/HAC/pha/paducah2/pgd_p1.html

<http://www.atsdr.cdc.gov/toxprofiles/tp11.pdf>

<http://www.atsdr.cdc.gov/toxprofiles/tp11-c5.pdf>

<http://www.atsdr.cdc.gov/toxprofiles/tp150-a.pdf>

<http://www.bt.cdc.gov/agent/hydrofluoricacid/basics/facts.asp>

<http://www.cdc.gov/niosh/ipcsneng/neng1250.html>

<http://www.cdc.gov/niosh/hhe/reports/pdfs/1994-0077-2568.pdf>

<http://www.cdc.gov/niosh/nmam/pdfs/chapter-m.pdf>

<http://www.cdc.gov/niosh/npg/nengapdx.html>

<http://www.cdc.gov/niosh/npg/npgd0334.html>

<http://www.cdc.gov/niosh/npptl/standardsdev/cbrn/apr/meetings/061802/pdfs/e-hazardanaly>

<http://www.cdc.gov/niosh/ocas/pdfs/arch/alliedc.pdf>

<http://www.cdc.gov/niosh/ocas/pdfs/arch/paducah2r1.pdf>

<http://www.cdc.gov/niosh/ocas/pdfs/arch/y1251.pdf>

<http://www.cdc.gov/niosh/ocas/pdfs/sec/harshaw/harshawer.pdf>

<http://www.cdc.gov/niosh/ocas/pdfs/tbd/weldon2.pdf>

<http://www.cdc.gov/niosh/pdfs/2001-133g5-2.pdf>

<http://msds.chem.ox.ac.uk/#MSDS>

http://msds.chem.ox.ac.uk/HY/hydrogen_fluoride.html