Advanced Fuel Cycle Cost Basis Report: Module K1 Deconversion of Depleted UF6 to Depleted Uranium Oxides

Nuclear Fuel Cycle and Supply Chain

Prepared for
U.S. Department of Energy
Systems Analysis and Integration
November 2021
INL/EXT-21-65142
Revision 0

K1.1 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004	All	**Version of AFC-CBR in which Module first appeared**: 2004 as Module K. Enrichment Plant DUF_6 Tails Conversion (Conversion and Disposal were combined). In 2006 AFC-CBR Module K was separated into K1, K2, and K3 to differentiate between deconversion of enrichment plant tails (K1) and deconversion of uranium products (RU) arising from aqueous reprocessing (K2) and pyroprocessing (K3). In 2015 K1 was split into K1.1 (deconversion) and K1.2 (disposal)
	2012	K1.1-All	**Latest version of module in which new technical data was used to establish unit cost ranges:** 2012 for deconversion
		K1.1-All	**New technical/cost data which has recently become available and will benefit next revision:** • Further analysis by USNRC to establish price for US Government (DOE) deconversion of tails from private US Enrichment plants • Published contract information for renewed **deconversion** operations contracts at DOE's Paducah KY and Portsmouth facilities**.** It should be noted that in early CY 2017 these two DOE-EM plants came under a new GOCO contractor: Mid-America Conversion Services. This organization is an LLC composed of US companies Atkins, Westinghouse, and Fluor.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

Page intentionally left blank

ACKNOWLEDGEMENT

This latest version of the Module *K1 Deconversion of Depleted UF6 to Depleted Uranium Oxides* is the result of the cumulative effort of many authors that have contributed to the Advanced Fuel Cycle Cost Basis Report (AFC-CBR). It is not possible to identify and acknowledge all those contributions to the AFC-CBR and this module. All the authors, including the four primary authors, fifteen contributing authors, the twelve contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. J. Hansen (INL) and E. Hoffman (ANL) can be contacted with any questions regarding this document.

jason.hansen@inl.gov; ehoffman@anl.gov

Suggested Citation:

DOE-NE Systems Analysis & Integration Campaign, *Advanced Fuel Cycle Cost Basis Report: Module K1 Deconversion of Depleted UF6 to Depleted Uranium Oxides*. Idaho Falls: Idaho National Laboratory, 2021.

Page intentionally left blank

CONTENTS

FIGURES

TABLES

ACRONYMS

ADU	ammonium diuranate
AREVA	name of a company
AVLIS	atomic vapor laser isotope separation
CHEMEX	chemical exchange
DOD	Department of Defense
DOE	U.S. Department of Energy
DOE NE	DOE Office of Nuclear Energy
DU	depleted uranium
DUF_6	
EMWG	Economic Modeling Working Group
EU	enriched uranium
FY	Fiscal Year
GDP	gaseous diffusion plant
HF	hydrogen fluoride
HF	hydrofluoric acid
INIS	International Isotopes
LES	Louisiana Energy Services, LLC
LLW	low-level waste
LWR	light-water reactor
MOX	mixed oxide
$MTDUF_6$	metric tonnes depleted uranium hexafluoride
MTU	metric tons of uranium per year
NATU	natural uranium
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
SWUs	separative work units
UDS	Uranium Disposition Services, LLC
UF_6	uranium hexafluoride
UOX	uranium oxide
USEC	United States Enrichment Corporation
WIT	What-it-takes

Page intentionally left blank

Module K1.1
Deconversion of DUF6 to Uranium Oxides

K1.1-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY22 update.**
- **Nature of this FY21 Module update from previous AFC-CBRs: Escalation only.**
- **Estimating Methodology for latest technical update (2012) from which this 2021 update was escalated:**
  - For DUF_6 to DUOx deconversion: Actual early operational data for DOE facilities and projected pricing data for private NRC-licensed facility.
  - It should be noted that Module K1-1 does not include geologic disposal of the packaged stable DU oxide. This activity is discussed in Module K1-2.

K1.1-1. BASIC INFORMATION

CONTEXT. During the late 1990s and into the 2000s, the US DOE studied disposition options for its 720,000 tonne UF_6 (as of 2007) inventory of depleted uranium (DU). DOE opted to deconvert its UF_6 and dispose of the resulting DU oxide, and plants were constructed at Paducah, KY and Portsmouth, OH to implement this strategy. The *December 2009 Advanced Fuel Cycle Cost Basis Report* (2009 CBR) reviewed the technology and cost analysis literature supporting this project. Having collected data from the DOE project and other domestic and foreign DU deconversion and disposal efforts, the 2009 CBR arrived at a cost estimate for **combined deconversion and disposal operations**.

The subsequent 2012 AFC-CBD update had two parts. First, it reviewed industry events and cost data released subsequent to the 2009 CBR. Second, it reconsidered the data reported in the 2009 CBR in order to break the combined cost estimate into separate estimates for deconversion and disposal. Separating the two processes allowed appropriate low, nominal and high cost estimates to be ascribed to each of the two steps. This is important since the disposal step has much more uncertainty associated with its implementation and cost than the deconversion step. It also permitted modelers to consider post-deconversion strategies other than near-surface disposal at a LLW facility, the option being pursued by the US and presented in detail as the reference disposal technology in the 2009 and 2012 documents

In the 2015 AFC-CBD document it was decided to separate Module K-1 into two parts, with Module K1-1 covering the DUF6 to depleted uranium oxide conversion process and Module K1-2 covering the oxide packaging and oxide geologic disposal. This Module K1 describes the former and includes some limited new information on deconversion technology and costs obtained in the 2012 to 2015 time frame. Recommended low, mode, high, and mean (expected value) unit deconversion cost projections in year 2015 dollars per kilogram of DU are presented. The reader should note that functional, historical, and operational information from the 2009 and 2012 AFC-CBD documents have been merged. For this reason, might be read like a series of newsletters, in which a later paragraph may seem to update or alter time-dependent information in a previous paragraph.

BASIC INFORMATION. Depleted uranium (DU) in the form of uranium hexafluoride (UF_6) is the by-product of the isotope separation processes used to enrich uranium above its natural isotopic abundance of 0.711 wt% U-235 for military and reactor applications (see Figure K1.1-1). Material balance demands that a stream of uranium of assay less than the natural feed isotopic abundance of 0.711 wt% U-235 also be produced. Because most uranium goes through the enrichment (isotope

separation) process (Module C) in the form of UF_6 and is withdrawn from the process in the same form using large cylinders, most depleted uranium still resides in this chemical form. The forms of depleted UF_4 U-metal, and UO_3 also exist in smaller amounts at some U.S. Department of Energy (DOE) sites. The U-235 assay of natural or slightly enriched uranium can also become depleted by virtue of being irradiated in a nuclear reactor (consumption of U-235 by the fission process). This fission-depleted uranium material is often found in the form of nitrate solutions or crystals or stable oxide powders from spent fuel reprocessing or plutonium recovery operations. (Handling of this reprocessed uranium material derived from burned natural uranium [NATU] or enriched uranium [EU] fuel is covered in Module K2.) In any case, the term "depleted" always indicates a U-235 isotopic assay of less than 0.711 wt% U-235.

In the U.S, most depleted uranium is in the form of DU_6, resulting from 60+ years of uranium enrichment operations conducted by three DOE enrichment (gaseous diffusion enrichment process) plants for military, research, and commercial nuclear plant use. Over 700,000 metric tons of DUF_6 reside at cylinder yards at the Paducah, Kentucky and Portsmouth, Ohio gaseous diffusion plant (GDP) sites; this material constitutes the largest DOE radioactive material legacy inventory (in terms of mass, not Curies) in the U.S. (see Figures K1.1-2 and K1.1-4). It should be noted that approximately 6,000 UF_6 legacy cylinders, formerly located at the Oak Ridge Gaseous Diffusion Plant site in Tennessee, were successfully transported to the Portsmouth site by the end of Calendar Year 2006 (Knoxville News Sentinel 2006).

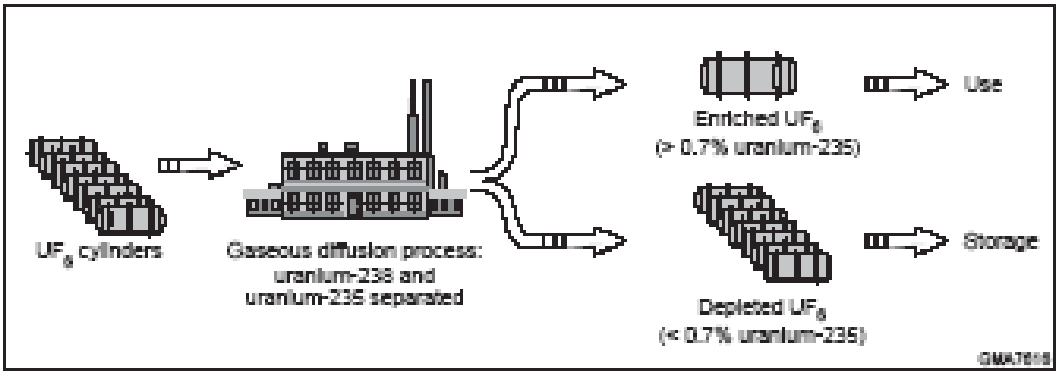

Figure K1.1-1. DUF_6 is the by-product of uranium enrichment (DOE 2001).

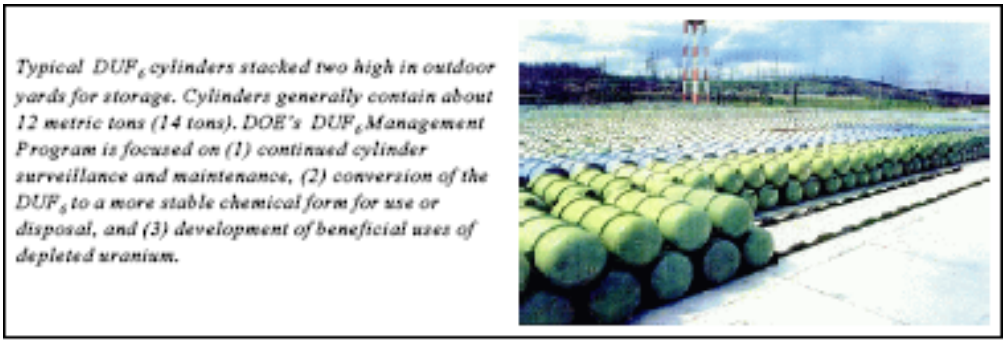

Figure K1.1-2. DUF_6 cylinders stacked for storage at a DOE gaseous diffusion plant site (DOE 2001).

As of January 2007, the following amounts existed at each site as government legacy material:

- Portsmouth Gaseous Diffusion Plant site: 250,517 metric tonnes depleted uranium hexafluoride ($MTDUF_6$)
- Paducah Gaseous Diffusion Plant site: 436,369 $MTDUF_6$.

The United States Enrichment Corporation (USEC) owns over 35,000 MTDUF$_6$ mostly at Portsmouth. The total for all owners is over 722,000 MTDUF$_6$. The U-235 isotopic assay of this material varies from 0.15 to 0.55 wt% U-235. (The tails assay for operation of the enrichments plants is determined by balancing feed [ore mining and milling + U_3O_8 to UF_6 conversion] costs against the cost of enrichment [separative work units (SWUs)]). Figure K1.1-3 shows how the U-235 assay of the depleted UF_6 inventory is distributed.

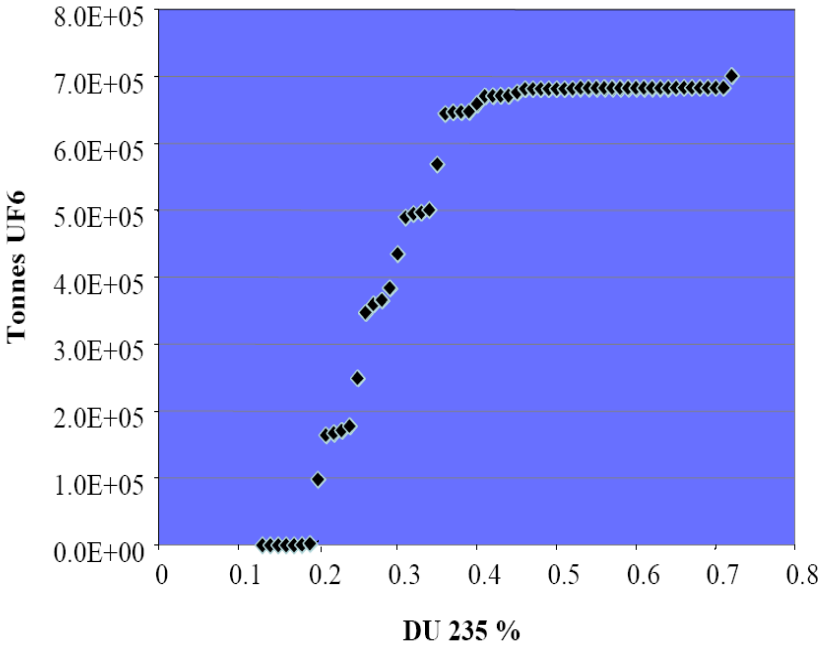

Figure K1.1-3. Cumulative distribution of DUF$_6$ metric tonnage versus U-235 assay.

The normal enrichment plant practice is to collect the DUF$_6$ from the GDP tails withdrawal systems in 14-ton steel-walled cylinders that are stacked and stored on the enrichment plant site. (This is still being done by USEC at the Paducah Gaseous Diffusion Plant, the only U.S. GDP operating today. USEC's tail cylinders represent nongovernment USEC DUF$_6$, which is not considered part of the government legacy described above but will in the future be treated by the same chemical processes as the government material.) In the early 1990s, some of the older legacy DUF$_6$ cylinders were found to be so degraded and corroded that oxidation compounds formed by the reaction of solid UF_6 with wet air were found on the surface of the cylinders. At this point, Congress and DOE realized that a serious water and air contamination problem could ensue if the DUF$_6$ storage problem were not fixed. (UF_6 vapor, produced by ambient or elevated temperature sublimation of solid UF_6, and moist air react to form gaseous hydrogen fluoride [HF, a very toxic and corrosive material] and UO_2F_2, a white, slightly radioactive powder that becomes airborne.) In the late 1990s, a program was initiated by the DOE Office of Nuclear Energy (DOE-NE) to begin looking at the options for long-term disposition of this legacy, including consideration of the best and safest chemical forms for future storage/disposal. These studies also included looking at possible beneficial uses of the depleted uranium, such as shielding for accelerator or nuclear facilities, containers for spent fuel or high-level waste, the diluent for mixed oxide fuel, re-enrichment, and semiconductors, with the realization that such uses may only utilize a fraction of the

DOE inventory. The official DOE Web site for DUF_6 has links to many DUF_6-related documents of use to the interested researcher (DOE 2001).[a]

It soon became apparent that the best route for permanent disposition of legacy DUF_6 is to convert it to a more stable and less-toxic chemical form, such as an oxide, and to isolate this form from the environment. In 2001, the U.S. nuclear and chemical industries were given the opportunity to propose and bid on the management, conversion, and disposition of the DOE-owned DUF_6 legacy material. Uranium Disposition Services, LLC (UDS), a consortium of three firms (Framatome-ANP, Duratek [now part of Energy Solutions, and Burns and Roe) was selected (DOE 2002) in 2002 to design and construct two DUF_6 to DU_3O_8 plants (one each at Paducah and Portsmouth [see Figure K1.1-4) and to contract for the disposition of the DU_3O_8 product in the same manner as is done for low-level waste (LLW). (Note that the conversion product is more accurately described as UOx [x~2.4 to 2.6], because there is some variation in stoichiometry.) The likely shallow burial resting place for this DU_3O_8 material, now to be packed in the old but washed-out UF_6 cylinders, was at that time designated to be Envirocare (a private firm now also part of the Energy Solutions consortium) in Clive, Utah, or the Nevada Test Site (NTS, a government site) near Beatty, Nevada. Construction of the two DOE-owned conversion plants commenced on July 31, 2004. More recently, it has been determined that DOE's LLW facility at the Nevada Test Site is the more economical and environmentally acceptable location for disposal of the DOE-legacy derived U_3O_8 (DOE 2004a and DOE 2004b). [b, c]

a. Author's note on beneficial uses: Early in the days of atomic energy, it was recognized that U-238, the isotope that constitutes over 99.29% of DU, could be readily converted in a reactor to the fissile isotope Pu-239. In fact, this is exactly what was done with the DU targets inserted into the U.S. plutonium production reactors that were located at Hanford and Savannah River for defense purposes. A fast neutron reactor fueled with plutonium could eventually produce enough new plutonium by irradiation of U-238 blanket assemblies that the fuel cycle would be self-sustaining with no requirement for new fissile material. Alvin Weinberg, former Director of Oak Ridge National Laboratory, once pointed out that the potential energy available from all the uranium in the DUF_6 cylinders in the storage yard of the nearby Oak Ridge Gaseous Diffusion Plant (K-25 or ORGDP) was the same as that available from a significant fraction of the U.S. reserves of coal.

b. Selection of NTS. Personal communication from Phillip McGinnis, ORNL DUF_6 Program Manager; April 2007.

c. Technical note: The two UDS facilities under construction will have to handle some DUF_6 that is slightly contaminated with the higher actinides plutonium and neptunium plus some fission product Tc-99. These contaminants were introduced into the GDP tails when the U.S. Atomic Energy Commission fed slightly impure reprocessed uranium into the GDPs. These two UDS plants are incorporating special safety features and procedures at some additional costs. Any new DUF_6 conversion plants supporting new enrichment capacity are not likely to have to deal with this problem, because virgin or unreprocessed uranium will only be fed to the enrichment facilities. Tc-99 and transuranic nuclides are potential problems for only a few cylinders after the DUF_6 is removed. Transferable Tc-99 and transuranic waste offer negligible additional radiological hazard in the proposed Portsmouth and Paducah processing plants and in the uranium oxides produced.

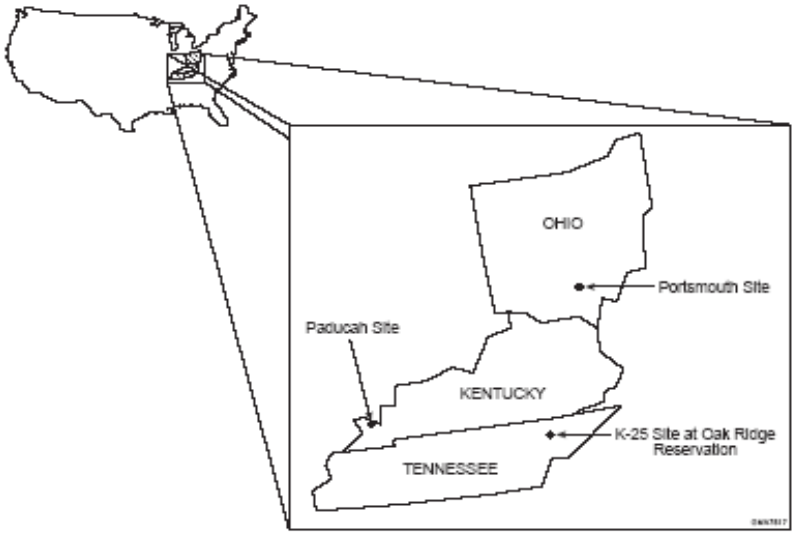

Figure K1.1-4. Source locations of U.S. DUF_6 stockpile (all DUF_6 now at Paducah and Portsmouth) (DOE 2001).

Currently these two deconversion facilities will handle only DOE legacy DUF_6 during most of their operating lives and that the same environmental/safety liability problem remains for the existing USEC DUF_6 stockpile and any future DUF_6 produced in new U.S. enrichment plants using UF_6 as feedstock. Disposition of the future DUF_6 stockpile was the major public licensing issue (NRC 2004) for the National Enrichment Facility, a Nuclear Regulatory Commission (NRC)-licensed (NRC 2003) gas centrifuge enrichment plant under construction in Hobbs, New Mexico, by the private firm Louisiana Energy Services, LLC (LES). Disposition of will also need to be addressed by the proposed NRC-licensed American Centrifuge Plant to be constructed by USEC at DOE's Portsmouth site (NRC 2004a) and AREVA's proposed gas-centrifuge Eagle Rock Enrichment Facility to be built near Idaho Falls, Idaho.

Being aware of DOE's problems at the three legacy GDP sites, stakeholders in the southeast New Mexico (location of LES plant) area do not want long-term storage of DUF_6 at the enrichment plant site. Because of such future enrichment commercial activity, it is very likely that new DUF_6 conversion facilities, such as those under construction by UDS at Paducah and Portsmouth, will have to be constructed either at or nearby the new enrichment plant sites, as add-on or schedule-extension capacity at Paducah or Portsmouth, or at new, Greenfield locations. It is very likely that private firms will finance, construct, and operate such plants, as opposed to the government contractor arrangement at Paducah and Portsmouth, which handles mainly government-owned materials. In fact, in February of 2005, LES and AREVA signed a memorandum of understanding that could lead to the possible construction of a private deconversion plant in nearby West Texas to support the proposed New Mexico enrichment facility (NEI 2005).

Additionally, International Isotopes of Idaho Falls, Idaho (INIS) has chosen Lea County, New Mexico as the site (640 acres) for the nation's first private depleted uranium deconversion and fluorine extraction facility (Platts 2009). According to their website this private facility will process ~7,000 MTU/yr and will be an NRC-licensed facility. Its nearness to the LES Enrichment Facility in New Mexico makes it likely that it will seek the business of handling LES tails. Its Idaho connection also makes it a candidate to handle future Eagle Rock (AREVA) tails. No costs for the project have been given, and the method of financing is still being evaluated by INIS (Earth Times 2009). However,

compared to other fuel cycle steps this one has relatively low technical, safety, and environmental risk; hence, total privatization should not be difficult.

A proposed laser-based enrichment process utilizing UF_6 as the feed material, such as the SILEX process being considered for deployment by General Electric near Wilmington, North Carolina will have the same tails disposal issue.

It is also very likely that this step will become mandatory in the front end of any fuel cycle where UF_6-based uranium enrichment is involved. This means that a definite market for this service will exist as long as enrichment markets are healthy. To eliminate or minimize transportation costs, the enricher might want to locate such conversion facilities adjacent to or as part of the new enrichment plant. France already does this with their DUF_6 to DU_3O_8 W-Plant located immediately adjacent to Cogema/Eurodif's Pierrelatte "Georges Besse" Gaseous Diffusion Plant. As mentioned earlier, LES is also known to be discussing DUF_6 conversion/disposition possibilities with existing nuclear and chemical firms. USEC, for their existing GDP and future gas centrifuge capacity at Portsmouth (American Centrifuge Plant), is very likely to contract with UDS for new conversion capacity at Portsmouth or queue their cylinders for conversion at the government facility after the legacy DUF_6 campaign is complete. (Note that federal law allows a government DUF_6 conversion plant to process nongovernment DUF_6 on a total cost-recovery basis. In fact, DOE has provided a unit cost estimate to LES for the provision of such services [Platts 2005a].)

K1.1-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

The DUF_6 conversion is a dry (nonaqueous) process that involves fluidized bed reaction of UF_6 vapor with steam and hydrogen to produce a flowable UOX powder, which is mostly U_3O_8. The process basically occurs in two steps:

UF_6 (v) + H_2O (v) → UO_2F_2(s) + 4HF (v)

$3UO_2F_2 + H_2 + 2H_2O \rightarrow U_3O_8 + 6HF$

where

(v) = vapor

(s) = solid

The hydrofluoric acid (HF) by-product has some value if it can be sold to an industrial user who is not concerned with the small (<10 ppm) amount of uranium that might be present in the HF. A nuclear user, such as a U_3O_8 (yellowcake) to natural UF_6 converter, might be interested in this HF. According to the 2007 DOE report UDS and Solvay Fluorides signed an HF sales agreement for an undisclosed amount of HF in May 2006. If all the HF cannot be sold, it may be necessary to convert the HF to stable, slightly uranium-contaminated CaF_2, which is relatively nontoxic, but which itself must be dispositioned, most likely by packaging and shallow burial as LLW. This disposal issue is also discussed in the 2007 DOE report (DOE 2007).

K1.1-3. PICTURES AND DIAGRAMS

The basic UDS process and material balance, as shown from the Site-Specific Environmental Impact Statement for Paducah (DOE 2004a), is shown on Figure K1.1-5 and described in Table K1.1-1. The process is very similar to the one used at the Framatome fuel fabrication facility at Richland, Washington, which converts enriched UF_6 to enriched UO_2 for use in light-water reactor (LWR) fuel (see Module D1). However, the throughput of the proposed DUF_6 plant is orders of magnitude higher than that of the Richland EUF_6 to EUO_2 plant.

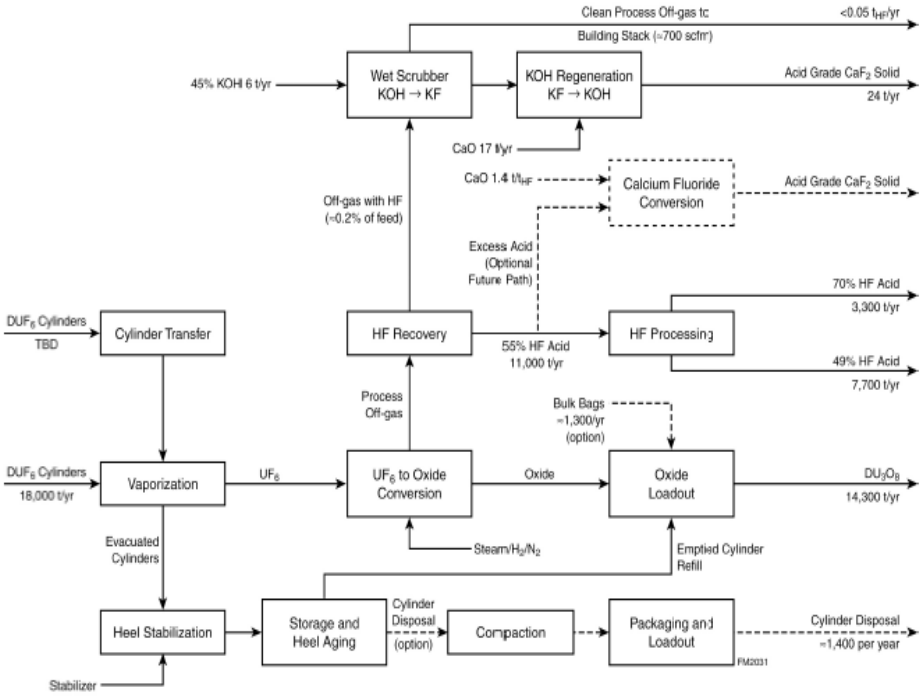

Figure K1.1-5. DUF_6 to DU_3O_8 conversion process (DOE 2007).

Table K1.1-1. Technical data for Paducah Uranium Disposition Services conversion facility (DOE 2007).

Parameter/Characteristic	Value
Construction start	2004
Construction period	2 years
Start of operations	2006
Operational period	25 years
Facility footprint	10 acres (4 ha)
Facility throughput	18,000 t/yr (20,000 tons/yr) DUF_6 (≈1,400 cylinders/yr)
Conversion products	
Depleted U_3O_8	14,300 t/yr (15,800 tons/yr)
CaF_2	24 t/yr (26 tons/yr)
70% HF acid	3,300 t/yr (3,600 tons/yr)
49% HF acid	7,700 t/yr (8,500 tons/yr)
Steel (emptied cylinders, if not used as disposal containers)	1,980 t/yr (2,200 tons/yr)
Proposed conversion product disposition (see Table 2.2-2 for details)	
Depleted U_3O_8	Disposal; Envirocare (primary), NTS (secondary)[a]
CaF_2	Disposal; Envirocare (primary), NTS (secondary)
70% HF acid	Sale pending DOE approval
49% HF acid	Sale pending DOE approval
Steel (emptied cylinders, if not used as disposal containers)	Disposal; Envirocare (primary), NTS (secondary)

[a] DOE plans to decide the specific disposal location(s) for the depleted U_3O_8 conversion product after additional appropriate NEPA review. Accordingly, DOE will continue to evaluate its disposal options and will consider any further information or comments relevant to that decision. DOE will give a minimum 45-day notice before making the specific disposal decision and will provide any supplemental NEPA analysis for public review and comment.

K1.1-4. MODULE INTERFACES

Front-end interface. The cost of storage of DUF_6 at enrichment plant sites should be assigned to the enrichment plant operational costs. If DUF_6 conversion is to be located away from the enrichment plant site, the cost of DUF_6 transportation (in 14-ton cylinders) by rail or truck should be assigned to the DUF_6 to DU_3O_8 conversion facility. Experience shows that these transportation costs are relatively small compared to processing costs. Module O discusses UF_6 transportation costs.

Back-end interface. (Note: These post-deconversion issues are described in more detail in the K1.2 DU Oxide Disposal Module.)

K1.1-5. SCALING CONSIDERATIONS

The UDS Paducah facility described above will have four parallel conversion lines in a single building (each line around 5,000 tons DUF_6 per year). It is now anticipated that these four lines will be replicated at Portsmouth. Up to this single-line capacity, a capital cost scaling exponent of 0.6 is probably appropriate. Beyond 5,000 tons per year, a 0.9-capital cost scaling factor can account for multiple lines in a single building. Operational costs are manpower intensive, and a scale factor of 0.9 for large plants should apply.

K1.1-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The 2012 CBR reported many data points for deconversion, disposal and combined deconversion and disposal costs. These are summarized in Table K1.1-2. Note that Table K1.2-1 includes cost estimates for deconversion as well as disposal; the full table was carried over from the 2012 CBR because it includes several estimates that combine deconversion and disposal costs. Also included in the table are cost estimates identified by Louisiana Energy Services while it was preparing the license application for its New Mexico enrichment facility [Louisiana Energy Services, 2004]. LES used this data to support of its argument that setting aside $5.5 ($7.04/kg U in 2012) per kg of DU it generated was sufficient to ensure that funds would exist to cover its disposition[d]. The new data presented in Section K1.1-7 concludes the table.

d. In the event, LES was required to post a bond of $7.15/kg of DU (2005 dollars).

Table K1.1-2. Summary of deconversion and disposal costs and estimates.

Facility or Author[1]	Scope	Reported Cost [$/kgU]	Basis Year	CPI Factor	**Unit Cost [2012 $/kgU]**	Comments & 2009 CBR Reference
Paducah	Both	3	2004	1.224	**3.67**	DOE 2007; HF credit included
(LLNL Study)	Both	5.38	2004	1.224	**6.59**	Elayat 1997 (Livermore)
(LES Study)	Both	5.5	2002	1.280	**7.04**	NRC 2003
N/A	Both	7.15	2005	1.189	**8.50**	Neary 2005; Bond posted to state of New Mexico to provide surety of disposal funds
(IEER Study)	Both	30	2005	1.189	**35.66**	Makhijani 2005a; IEER position on appropriate value of bond
NTS	Disposal	11.6	2003	1.248	**14.47**	DOE 2005; Thorium disposal. Costs in $/kg Th.
(Diehl Study)	Disposal	110	2007	1.120	**123.21**	Diehl 2007; Discounted as unrealistic
(LLNL Study)	Deconversion	2.64	2002	1.280	**3.38**	HF Sale
(LLNL Study)	Deconversion	3.39	2002	1.280	**4.34**	HF Neutralization
(LLNL Study)	Disposal	1.71	2002	1.280	**2.19**	Trench Disposal
(LLNL Study)	Disposal	2.42	2002	1.280	**3.10**	Vault Disposal
(Claiborne Energy Center Study)	Deconversion	4.93	2002	1.280	**6.31**	Based on quote by Cogema in 1993 for services at Tricastin
(Claiborne Energy Center Study)	Disposal	1.81	2002	1.280	**2.32**	From estimate provided by Urenco in 1993
Data added in 2012 update						
INIS	Deconversion	14.47	2012	1.000	**14.47**	Smaller (Phase 1) plant
INIS	Deconversion	7.35	2012	1.000	**7.35**	Larger (Phase 1&2) Plant
Paducah	Both	5.33	2012	1.000	**5.33**	If a plant identical to Paducah was privately built & operated
INIS	Disposal	1.41	2012	1.000	**1.41**	Low estimate
INIS	Disposal	3.83	2012	1.000	**3.83**	High estimate
1. (Study) = based on a generic plant and process, not tied to a specific facility						

Publicly available cost information on this new step of the fuel cycle has evolved over the last 8 years. The Paducah GDP formerly made depleted uranium compounds and metal from DUF_6 for defense applications from the mid-1950s until the 1980s; however, the costs and other technical information on this operation are still classified. Among the sources of cost data are initial cost studies for the former DOE-NE DUF_6 program (now a DOE Environmental Management [EM] project), DOE-UDS contract information, and proceedings related to the NRC licensing of the LES National Enrichment Facility. All this cost information is essentially in the form of projections. No such facilities are yet operating on a large scale in the U.S.; hence, no historical data are available. (The first DOE-UDS conversion operation is slated for late 2009.) The cost figure of merit of interest for this step is the unit cost in $/kg U (as DUF_6) converted and dispositioned for plants of capacities in the several thousands of metric tons of uranium per year (MTU/yr). Table K1-1-1 shows the throughput and other relevant technical data for the proposed Paducah facility. (The Portsmouth facility will be nearly identical.) Such plants consist of multiple identical process trains or lines of a few thousand MTU/yr each, thus any plant scaling/expansion beyond one line is achieved by line replication. In 2002, capital costs for such plants were expected to be in the $100+ million each range, which is relatively low for nuclear facilities with similar footprints or process areas.

The 1997 Livermore report (Elayat et al. 1977) contains the first economic analysis projection performed for DOE DUF_6 management after the program was formed in DOE-NE. It looked at several end products (such as U, UO_2, U_3O_8, and the sale of by-product HF). Costs were expressed as lump-sum discounted life-cycle costs. The closest option considered by Lawrence Livermore National Laboratory to the one finally selected by DOE in 2002 is that of dry conversion to U_3O_8 followed by burial in shallow trenches. It was assumed that 28,000 MTU/yr be processed for 20 years in a single large privately owned and financed plant. At a discounted (7% real) life-cycle cost, including design, construction, operations, and decommissioning of $758M for the whole conversion/disposal program (not including revenues from by-product sales, which decrease the net unit cost by a few percent), a projected unit cost of $5.38/kgU was calculated by Oak Ridge National Laboratory from the Lawrence Livermore National Laboratory data in August 2004.

As will be seen, this unit cost is higher than the price derived from the life-cycle costs proposed by the winning bidder for the DOE legacy work. However, the latter considered revenues from HF sales, a smaller building and throughput, no financing charges (government funds to construct), and very competitive negotiated disposal fees (for shallow burial of U_3O_8). Therefore, the analyst for Module K1 believes that the calculated $5.58/kgU ($6/kgU in 2007 $) estimate is a reasonable projection in light of the lower Fiscal Year (FY) 2001 unit cost estimates made for the DUF_6 to DU_3O_8 government-owned plants now under construction at Paducah, Kentucky, and Portsmouth, Ohio.

The $5+/kgU projected cost is supported by another fuel cycle study (Bunn et al. 2003). One of the contentions brought up by interveners is the disposition of DUF_6 tails from the proposed LES National Enrichment Facility to be located in southeastern New Mexico. The interveners question the validity of the $5.50/kgU cost of disposal number put forth by LES in the licensing documentation (NRC 2003) submitted to the NRC. (This was one of the admissible contentions brought forth by the interveners). Oak Ridge National Laboratory believes a number around this figure to be a credible projection for a privately owned and financed facility. It is surmised that LES, a private corporation, probably based their calculation of this unit cost on what it would cost for them to do these operations (deconversion of 7,800 $MTDUF_6$/yr) as part of the enrichment step (i.e., as a fully amortized add-on facility to their gas-centrifuge plant). If the $5.5/kgU unit cost was rolled into the price of enrichment, the latter $/SWU price would have to be increased on the order of 10%. Because of the highly competitive enrichment market, LES's reluctance to commit to the additional step of DUF_6 conversion/disposition at this time is not unexpected. In a March 2005 letter (Platts 2005a), DOE indicated that its projected charge to LES to perform this service would be $3.34/kg$DUF_6$ or $4.91/kgU in a government facility based on a pro-rata share of the capital and operating costs of the two UDS facilities under construction. NRC found another LES estimate of $4.68/kgU to be reasonable (Platts 2005b). In a June 2005 agreement with the State of New Mexico, LES is being required to put up a bond of $7.15/kgU (Neary 2005). This unit cost is likely to be closer to the unit cost that will ultimately be realized later in this decade, especially as costs for the UDS facilities surpass the original estimates.

Antinuclear groups such as Institute for Energy and Environmental Research (Makhijani and Smith 2005a) suggest that even this is too low a value, and that values as high as $30/kgU (including disposal) should be used for the bond (Makhijani and Smith 2005b). Such a high value would imply that shallow burial of the DU_3O_8 would not be allowable because of radon considerations and that deep burial in a mine or geologic repository would be required. Hopefully, all nuclear fuel cycle nations with enrichment plants will ultimately agree that DUF_6 conversion/disposition is environmentally necessary and will add the needed DUF_6 conversion/disposal capacity, which will eventually level the playing field for enrichment pricing. A new path for DUF_6 disposition is now being pursued (i.e., re-enrichment of the tails to produce natural assay feed). Rising uranium ore and conversion prices in the early 2000s have convinced the Bonneville Power Administration that such a scheme is economic (Platts 2005c). The

economics of tails re-enrichment will be discussed in more detail in Module C2 and is also the subject of ongoing study by DOE, as indicated by recent issuance of a uranium management plan (DOE 2008).

The unit cost from a proposed UDS facility can also be roughly calculated from contract announcement (DOE 2002) information that mentions the $5.58/kgU value of the contract (2002 dollars), the 700+ thousand metric ton inventory (to be processed over 20 years), and the need to design and construct the two plants in 3 years and operate them for 5 years. (Additional years will be under a new contract.) The following Oak Ridge National Laboratory-generated spreadsheet (see Table K1-2) was used in the early part of this decade to project the unit cost from the proposed Paducah government-owned/contractor-built and operated conversion facility.

The calculation assumes a low (3.8%) government real discount rate and assumes that the 5-year constant dollar operating costs are maintained over the additional 15 years of plant production. The capital cost is assumed to be amortized over the 20 years of operations. Although the government does not amortize in the same sense as a private enterprise, an imputed amortization can be used to calculate the same unit cost that would be derived by discounting government cash flows at the same low discount rate.

As expected, a government financed plant was projected to convert and disposition DUF_6 at a lower unit cost, (i.e., a projected $3/kgU unit cost as opposed to $5+/kgU for the private facility). For future fuel cycles, it should be assumed that private industry will finance, own, and operate such facilities. With process improvements and operational learning, a constant dollar price of $5/kgU for the private facility should certainly be realizable if deployment risks are minimized and shallow U_3O_8 burial is allowed. This cost is in line with Bunn, et al.'s estimate (Bunn et al. 2003) for producing fast reactor blanket feed material, presumably DU metal or DUO_2 feed to the fuel/blanket fabrication plant, of $6/kgU. The earlier DOE/Lawrence Livermore National Laboratory studies show that producing DU metal or DUO_2 is somewhat more expensive than producing DU_3O_8. This is because batchwise reduction operations are needed as opposed to the continuous process for DU_3O_8 production.

It should be noted that as of summer 2009 the two UDS plants are ending their construction phase and beginning start-up procedures. The actual construction cost has been reported (IPA 2009) to be nearly $600M for both plants, an amount nearly double that (~$300M) projected at the time design was initiated. If the government were to amortize this higher capital cost across future plant production, it is likely to add at least $1/kgDU to the unit production cost.

Another very useful "actual" cost number relevant to DU conversion and geologic disposition is that for the packaging, transportation, and disposal of 7 million pounds (1.29 million kg Th) of U.S. government surplus thorium nitrate pentahydrate [$Th(NO_3)_4*5H_2O$] powder. This material has radiological and morphological properties very similar to natural or depleted uranium, and was formerly warehoused at the Department of Defense (DOD) depots in Curtis Bay, Maryland and Hammond, Indiana. In the period 2004--2005 this material was repackaged, transported, and disposed by geologic shallow burial at the DOE Nevada Test Site, now renamed Nevada National Security Site. (The Nevada Test Site is also likely to receive DU_3O_8.) The cost for this entire effort was $15M in 2003$ or a unit cost of $11.6/kgTh. In 2008 dollars this is $13.5/kgTh. Documentation of this activity can be found in Hermes 2001, Hermes 2003, Hermes 2006, and DOD 2005. The disposition rate (MT/yr) for this material is over an order of magnitude smaller than that projected for DU. Therefore, it is not surprising that a somewhat higher unit cost for disposing of thorium was experienced as compared to the projected unit cost of disposition of DU materials. Further discussion of thorium can be found in Modules A2 and D1-8 of this report.

K1.1-7. DATA LIMITATIONS

The following considerations are relevant to depleted-uranium materials in the fuel cycle:

1. If non-UF_6 based enrichment processes are eventually realized, such as atomic vapor laser isotope separation (AVLIS) or chemical exchange (CHEMEX), the chemical form of DU from the

enrichment plant will be different. Conversion costs for metal DU product from AVLIS, for example, are likely to be somewhat higher than for conversion of DUF_6. In Table K1-2, all costs are limited to DUF_6-based processes.

2. If reprocessed uranium is ultimately fed back to enrichment plants, a possibility from closed fuel cycles, very small amounts of actinides and fission products might contaminate these "secondary" tails. Dealing with this problem and its safety consequences could cause a unit cost increase for DUF_6 conversion/disposal. Future experience with the UDS (Paducah and Portsmouth) plants should provide better cost data, since some of the U.S. GDPs handled RU in periodic re-enrichment campaigns and some DUF_6 cylinders are likely to contain such minor constituents.
3. Unit conversion/disposal costs for natural assay or enriched UF_6 up to approximately 0.9% U-235 are likely to be close to those for DUF_6. (It is unlikely one would dispose of these materials unless irradiation or contamination has driven the fission product, transuranic, or U-236 levels up to a level at which recovery of pure uranium products would not be economic.) Up to this 0.9% U-235 assay, nuclear criticality under light-water moderation is not a concern for processing or disposal. A UREX-based reprocessing plant (Module R1) will produce such low enrichment U products as part of its multiple output streams (see Module K2).
4. The disposition of weapons-grade plutonium by use of LWRs burning mixed oxide fuel may use 0.5 to 2% of the government DUF_6 stockpile. DUO_2 is the preferred diluent for the plutonium in LWR mixed oxide (MOX) fuel (i.e., ~96% DUO_2 and 4% PuO_2). A conversion facility will be needed to produce DUO_2 from DUF_6 for the U.S. plutonium disposition program, and Framatome (AREVA) has proposed such a facility for its Richland, Washington facility. The DUO_2 powder produced will have special quality assurance and fuel qualification requirements far exceeding those of dry-processed U_3O_8 or UO_2 powder destined for disposal. A "wet" or "dry" processed DUO_2 powder, such as from the Framatome ammonium diuranate (ADU) wet process, that is capable of meeting the present MOX fuel irradiation specification for the U.S. plutonium disposition program will have a unit cost considerably higher than the $5/kgU proposed for dry-processed U_3O_8, which will ultimately be buried. The conversion cost for this special MOX-grade powder will likely be in the $30 to $70/kgU range. This cost is eventually absorbed in the overall cost of the MOX fuel (Module D1-2). DOE is presently (2007) in the process of seeking fuel fabricators who might want to provide this DUO_2 on a contract basis.
5. Another beneficial use that would consume much of the DUF_6 inventory is the use of DUO_2 rough pellets as filler material in the final disposition spent fuel containers for the proposed Yucca Mountain repository. Since over eons, Pu-239 decays to U-235, the depleted uranium material could isotopically dilute any leached U-235 and prevent future repository criticality. In essence, such an application would be rejoining the U-238 with the remaining unfissioned U-235 (in the spent fuel) from which it was originally separated. This concept is discussed in Forsberg 2000 and Forsberg and Doyle 2006, but is not presently part of the baseline Yucca Mountain spent fuel repository program. The author is not aware of any cost studies on this concept. An INL study (Hertzler and Nishimbo 1994) reports that DU use in casks would cost $22.80/kg UF_6.
6. If uranium ore prices rise significantly and SWUs remain cheap, re-enrichment of DUF_6 makes eminent economic sense. The Russians are already doing this with DUF_6 from Urenco's European Centrifuge Enrichment plants (Diehl 2007). Russian SWUs from fully amortized centrifuge plants are available at a very low cost. USEC has also recently requested that DOE make available its higher assay tails for re-enrichment at their Paducah facility (Nuclear Fuel Cycle Monitor 2008). At 2007 EUF_6 prices, with their high U_3O_8 component, USEC could realize significant profit from the use of this essentially free tails feed material, since the costs of additional enrichment from ~0.4% U-235 to 0.71% U-235 (natural feed equivalent) are comparable to the purchase today (at over $130/kgU) of converted U_3O_8.

7. An unfavorable ruling from the NRC or an NRC ruling requiring stringent radon mitigation measures on shallow burial of DU_3O_8 at commercial LWR disposal sites, such as Envirocare, could significantly impact the unit cost, because a more expensive burial solution would be needed. Such a ruling might force burial at a non-NRC regulated site such as DOE's Nevada Test Site (Makhijani and Smith 2005b).[e] Even at a government site, such as Nevada Test Site, some radon amelioration measures are likely to be required. As mentioned earlier, NTS is now the preferred disposal option.

In general, the DUF_6 conversion/disposal step of the fuel cycle can be placed in the viable-commercial category of technology readiness.

e. Personal communication from D. W. Lee, Oak Ridge National Laboratory.

Table K1.1-3. Unit DUF_6 conversion/disposal cost from a government plant.

Proposed Government DUF6 Conversion Facility at Paducah		
Plant annual capacity	12100	MTDU/yr
Economic life	20	yrs
Design and permitting cost	16	$M
Site-related costs	10	$M
Facility construction cost	84	$M
Total base capital cost including contingency	110.0	$M
Imputed interest during construction (2 yrs to construct)	5.5	$M
Total capital cost (2002$)	**115.5**	$M
Annual ops cost breakdown:		
Conversion plant operations	15.6	$M/yr
U3O8 packaging/disposal	10.4	$M/yr
Total annual operations cost	26.0	$M/yr
Operations contribution to levelized cost of product/service	2.15	$/kgU
Discount rate for government project (real)	3.80%	
Capital recovery factor (fraction per yr of ops)	0.0723	
Annual payments to recover capital cost of plant over life	8.35	$M
Capital portion of unit product cost	0.69	$/kgU
Total levelized product cost (2002$)	**2.84**	**$/kgU**
In 2004$:	**3.0**	**$/kgU**
Effect on Enrichment Price:		
W/P ratio for reload PWR enrichment (3.78% U-235)	7.46	
SWU/P ratio for same (P=1)	4.86	
Additional conv/disp $ to produce 4.86 SWU	21.18	$
Addition to SWU price to cover deconversion/disposal:	4.36	$/SWU

K1.1-8. COST SUMMARIES

No DUF_6 disposition life-cycle cost data are publicly available in the Advanced Fuel Cycle standard code-of-accounts format. It is likely that UDS has such data in their conversion facility detailed design in the work breakdown structure or code-of-accounts system. However, it is available only to their DOE-EM customer.

In summary, a commercial (privately financed) conversion/disposal program is projected to disposition DUF_6 at $6.00/kgU (in 2008 dollars). And a government program is projected to disposition the same material at $4–$6/kgU, depending on discount rate assumptions. Both of these assume that shallow burial as LLW is permissible and readily available in the near term. For reference purposes, the private plant with technology improvements is the most likely path for non-legacy DUF_6 in future fuel cycles. Recent experience with DOE projects, such as the UDS Deconversion Plants, the Savannah River MOX Fuel Fabrication Facility, the Hanford River Protection Project, and the Tritium extraction facility, indicated that "in-construction" projections of or completed facility "actuals" of capital and operating costs usually significantly exceed early preconstruction cost projections. The $11/kgU selected unit cost value should reflect such conversion facility cost escalation and likely prolonged regulatory and contracting difficulties with DU_3O_8 shallow burial. Ultimate project completion and success, however, is still assumed.

2012 Update Table K1.1-4 lists deconversion plants operating and under construction around the world in 2012. Following the commissioning of three plants in 2010, operating deconversion capacity stands at over 41,000 tU in UF_6/year. As of 2007, approximately one-quarter of the ca. 1.5 million tonnes of DU generated around the world have been deconverted (World Nuclear Association, 2012).

Table K1.1-4. Nominal 2012 deconversion capacities, plants operating and under construction.

Operator / Plant	2012 Capacity [tU in UF_6/year]	Notes
AREVA / Tricastin, France	13,500	Opened 1984
Uranium Disposition Services / Portsmouth, OH	9,100	Operations commenced 2010
Uranium Disposition Services / Paducah, KY	12,200	Operations commenced 2010
Rosatom / Zelenogorsk, Russia	6,800	Operations commenced 2010
International Isotopes, Inc./Hobbs, NM	Pending	NRC license decision pending in late 2012; Construction of Phase 1 (2,200 tU/yr) to begin. Planned Phase 2 would bring capacity to 6,600 tU/yr*
TOTAL	41,600 operating; 43,800-48,200 operating & pending	

Data source: WNA 2012

The International Isotopes (INIS) plant is unique in two ways. INIS has acquired assets from the UF_6-to-UF_4 component of the shutdown Sequoyah deconversion plant and is transporting these to its Hobbs, NM site. It also utilizes a different process than the other facilities: INIS' Fluorine Extraction Process (FEP) focuses on recovering high-purity, high value fluorine compounds, in particular SiF_4 (International Isotopes Fluorine Products, 2009).

Construction and operating cost estimates for the facility are available from Ref. (NRC 2011) and decommissioning cost forecasts from (International Isotopes Fluorine Products, 2009). These allow the unit deconversion cost estimates shown in Table K1-2 to be developed. But the acquisition of existing capital stock from Sequoyah may mean that the capital costs are lower than would be the case for an entirely new facility. On the other hand, estimates of proceeds from the sale of fluorine co-products are not available and thus not included in the deconversion unit cost estimate. INIS will likely receive greater co-product revenues as a result of its FEP process than is the case for other plants that just market a lower-purity HF co-product.

INIS plans to stage the construction of its facility. Construction of Phase 1 is to begin in 2012, with a Phase 2 expansion that would triple capacity to follow several years later. Refs. (International Isotopes Fluorine Products, 2009) and (NRC 2011) provide cost data sets for Phase 1 only as well as Phases 1 and

2 together. Since the data is illustrative of economies of scale benefits that accrue when the capacity is tripled, both sets are shown[f]. Unit deconversion costs, in year 2012 dollars per kg U, are calculated according to the Generation-IV Economic Modeling Working Group (EMWG) methodology referenced and applied in the 2009 CBR.

This facility will be the first privately owned and operated deconversion plant in the world. Hence the real interest rate of capital recommended by the EMWG for private facilities, 10%, was applied. This leads to unit deconversion costs of $7.4/kg U for the large (Phase 1&2) plant and $14.5 for the small (Phase 1 only) alternative, considerably higher than corresponding values for government-owned plants. For example, in the 2009 CBR the EMWG methodology was applied to the Paducah facility but with an interest rate of capital of 3.8%. This analysis led to a deconversion cost of $3.0/kg U in 2004 dollars ($3.7/kg U in 2012 dollars). Therefore, for illustration, the unit deconversion cost for Paducah if it had faced an interest rate of capital of 10% is also shown in Table K1-2. The resulting cost, $5.3/kg U, is close to the $7.4/kg U for the large INIS plant option, but the Paducah estimate includes a credit for the sale of HF. Further economies of scale may also play a role, as the capacity of Paducah is almost 50% greater than that of even the large INIS option.

Table K1.1-5. Unit deconversion costs for INIS and a privately-built plant identical to Portsmouth.

		INIS - Phase 1 Only	INIS - Phase 1&2	Paducah[1]
Overnight Capital	$[2]	1.29E+08	2.07E+08	1.64E+08
Operating	$/yr	1.71E+07	2.43E+07	2.91E+07
Decommissioning	$	1.45E+07	1.72E+07	5.82E+07
Plant Capacity	tonne U/yr	2.23E+03	6.63E+03	9.13E+03
Constr. Time	yr	2.00	2.00	2.00
Operating Lifetime	yr	40.00	40.00	38.00
Interest Rate of Capital	1/yr	0.10	0.10	0.10
Sinking Fund Rate[3]	1/yr	0.10	0.10	0.10
Unit Deconversion Cost	**$/kg U**	**14.47**	**7.35**	**5.33**

1. Private-sector financial assumptions applied to Portsmouth facility capital & operating costs.
2. Year 2012 dollars. Converted from year 2009 dollars for INIS and 2004 dollars for Paducah.
3. Used to amortize decommissioning costs. See 2009 CBR for methodology discussion & reference.

The **mode** estimate, $6/kg U, lies somewhat below the projected cost for the privately operated INIS facility but above the projections for the publicly-owned Paducah plant. As mentioned in the 2009 CBR, the cost estimates for Paducah and Portsmouth appearing in their license applications are known to be optimistic, although realized costs are not yet available. It is likely that the INIS plant would recover significant value, perhaps $1-2/kg U, from sale of fluorine byproducts. This benefit is not reflected in the estimate of Table K1-1-5, and moreover the 10% interest rate of capital may be considered conservative.

The **low cost** estimate, $4/kg U, is in line with the price quoted by Areva predecessor Cogema for deconversion services in France as well as the most optimistic costs in Table K1.1-5. It is considered to reflect capitalization on economies of scale benefits, ongoing technological advancement, and strong recovery of value from fluorine byproducts.

f. The references give ranges for several of the capital, operating and decommissioning cost components. For this analysis, values at the middle of the range were used. Costs in the references were given in 2009 dollars and were converted to 2012 dollars using the CPI (scaling factor: 1.074). In addition, to simplify the unit deconversion cost calculation for the combined Phase 1 & 2 case, it was assumed that Phase 1 & Phase 2 were constructed simultaneously.

The **high cost** estimate, $8/kg U, is slightly higher than the estimate for the private INIS facility and close to the value of the bond LES was required to put up to ensure that disposition of its depleted uranium was funded (although that reflects disposal as well). It is more likely to come about if governments phase out their current major role in the industry. It may further reflect a future industry with many small to medium-sized private providers, or a handful of large ones who are able to exert market power. Finally, weak cost recovery from byproduct sale may contribute to this outcome.

Table K1.1-6. "What-it-takes" (WIT) Table (2012$).

	Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
Deconversion	$6/ kg U	$4/ kg U	$8/ kg U	$6/ kg U
Disposal	$4/ kg U	$2/ kg U	$22/ kg U	$4/ kg U
Total (2012 values)	$10/kg U	$6/ kgU	$30/ kgU	$10/ kg U
	2009 CBR Values for combined deconversion and disposal:			
Both	$11/kg U	$6/kg U in UF_6	$50/kg U in UF_6	$11/kg U in UF_6

The data in Table K1.1-6 now needs to be updated to year 2020$ for deconversion. It should also be noted that recent data from BWXT Conversion Services[g] (BWXT2014) indicates that their operations costs fall well within the range of Table K1.1-6. This was calculated by dividing their $428M 5-year (2011-2015) contract cost by the approximately 100,000 MTDUF6 they have already processed to date. The escalation factor from 2012$ to 2017$ is only 1.134, so the rounded escalated 20207$ unit costs are just slightly above the 2012 values when rounded to the nearest tenth of a dollar. Figure K1.1-6 and Table K1.1-7 show the triangular distribution and defining parameters for the unit deconversion cost and its uncertainty. The mean or "expected value" of the distribution is $6.58kgU in 2022$. For the 2020 table and figure below an escalation factor of 1.134 (from 2012$), representing escalation based on the escalation table in the "Escalation Considerations" Section of the Main part of this report, has been assumed.

Table K1.1-7. "What-it-takes" (WIT) Table (2020$).

	Reference Cost(s) Based on Reference Capacity	Low Cost 2020$	Mode Cost 2020$	Mean Cost 2020$	High Cost 2020$
Deconversion only (without oxide geologic disposal)	$6/ kg U in 2012$	$4.54/ kg U	$6.8/ kg U	$6.8/ kg U	$9.1/ kg U

g. BWXT conversion services was the GOCO (Government-Owned Contractor-Operated) contractor for the Paducah and Portsmouth deconversion facilities prior to selection by DOE of Mid-America conversion services in September 2016.

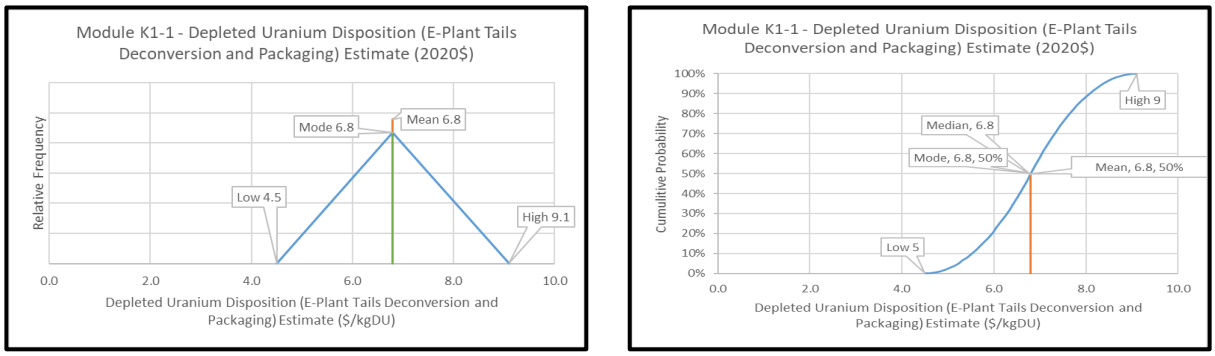

Figure K1.1-6. Depleted U deconversion estimated unit cost frequency distribution (2020$).

K1.1-9. SENSITIVITY AND UNCERTAINTY ANALYSES

Not presently available.

K1.1-10.REFERENCES

BWXT 2014, BWXT Announces 428 million dollar Five year Contract, www.bwxtconversionservices.com

Bunn, M., et al., 2003, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Cambridge, Massachusetts, Project on Managing the Atom, Harvard University, DE, http://belfercenter.ksg.harvard.edu/publication/2089/economics_of_reprocessing_vs_direct_disposal_of_spent_nuclear_fuel.html, Web page accessed August 25, 2009.

Diehl, Peter, 2007, *Re-enrichment of West European Depleted Uranium Tails in Russia,* Ecodefense Russia, June 2007, http://www.wise-uranium.org/edumu.html, Web page accessed August 25, 2009.

DOD 2005; Department of Defense Revolving Funds – Justification/Overview: FY 2006/2007 President's Budget Estimates; February 2005.

DOE, 2001, *DUF_6 Management Information Network*, U.S. Department of Energy, www.ead.anl.gov/uranium.html, Web page accessed August 25, 2009.

DOE, 2002, *Press Releases*, "Department of Energy Selects Uranium Disposition Services for Uranium Hexafluoride Conversion Plants in Ohio and Kentucky," U.S. Department of Energy, August 28, 2002.

DOE, 2004a, *Record of Decision for Construction and Operation of a Depleted Uranium Hexafluoride Conversion Facility at the Paducah, Kentucky Site*, U.S. Department of Energy, July 20, 2004, http://web.ead.anl.gov/uranium/pdf/PadROD.pdf, Web page accessed August 25, 2009.

DOE, 2004b, *Record of Decision for Construction and Operation of a Depleted Uranium Hexafluoride Conversion Facility at the Portsmouth, Ohio Site,* U.S. Department of Energy, July 20, 2004, http://web.ead.anl.gov/uranium/pdf/PortROD.pdf, Web page accessed August 25, 2009.

DOE, 2005, *Site Specific Environmental Impact Statement for Depleted Uranium Conversion Facility to be Constructed at Paducah, Kentucky*, DOE/EIS-0359, U.S. Department of Energy, http://web.ead.anl.gov/uranium/pdf/PAD-Cover.pdf, Web page accessed August 25, 2009.

DOE, 2007, *Draft Supplement Analysis for Location(s) to Dispose of Deplete Uranium Oxide Conversion Product Generated from DOE's Inventory of Depleted Uranium Hexafluoride*, DOE/EIS-0359-SA1 and DOE/EIS-0360-SA1, U.S. Department of Energy, March 2007.

DOE, 2008, *Excess Uranium Inventory Management Plan*, U.S. Department of Energy, December 16, 2008

Earth Times 2009, "International Isotopes Inc. Announces Results of the Annual Meeting and Provides an Update on Its Depleted Uranium Processing and Fluorine Extraction Process Plant," July 21, 2009, http://www.earthtimes.org/articles/show/international-isotopes-inc-announces-results,898822.shtml, Web page accessed August 2009.

Elayat, H., J. Zoller, Lisa Szytel, 1977, *Cost Analysis Report for the Long-Term Management of Depleted Uranium Hexafluoride,* UCRL-AR-127650, Lawrence Livermore National Laboratory, May 1977, http://web.ead.anl.gov/uranium/documents/paddeis/index.cfm, Web page accessed August 25, 2009.

Fahys, Judy, Salt Lake Tribune, 2009, "Ruling Clears Way for Store Depleted Uranium," March 18, 2009.

Forsberg, C. W., 2000, "Effect of Depleted-Uranium Dioxide Particulate Fill on Spent-Nuclear Fuel Waste Packages," *Nuclear Technology*, Vol. 131, No. 3, September 2000, pp. 337–353.

Forsberg, C. W. and Dole, L. R., 2006, *Cermet Spent Nuclear Fuel Casks and Waste Packages,* Proceedings of the Materials Research Society, Scientific Basis for waste Management, November 27–December 1, 2006, Boston, Massachusetts.

Hermes, et al. 2001, "Thorium Nitrate Material Inventory Definition Report," Oak Ridge National Laboratory, ORNL/TM-2000/163, June 2001 (Official Use Only).

Hermes, et al 2003, "Thorium Nitrate Stockpile – From Here to Eternity," Paper presented to the Waste Mnagement '03 Conference; Tucson, Arizona; February 23–27, 2003.

Hermes, 2006, "Removing the Source Term – Thorium Nitrate Disposal at the Nevada Test Site"; W.H. Hermes; Oak Ridge National Laboratory; Paper presented to the Health Physics Society 2007 Midyear Topical meeting, Knoxville, Tennessee, January 21–24, 2006.

Hertzler and Nishimbo, 1994, "Depleted Uranium Management Alternatives," INL Report EGG-MS-11416, 1994.

International Isotopes Fluorine Products, Inc., "Fluorine Extraction Process & Depleted Uranium De-conversion Plant Environmental Report," technical report ER-IFP-001 Rev A, December 2009.

Knoxville News Sentinel, 2006, *DOE Removal Project Done Early: Uranium Hexafluoride Relocated within Budget, Reducing Radiation Hazard,* December 18, 2006.

Louisiana Energy Services, "National Enrichment Facility Environmental Report," Revision 2, July 2004.

Makhijani, A. and B. Smith, 2005a, "Costs and Risks of Management and Disposal of Depleted Uranium from the National Enrichment Facility Proposed to be Built in Lea County New Mexico by LES," *Institute for Energy and Environmental Research*, version for public release redacted March 20, 2007, http://www.ieer.org/reports/du/LESrptfeb05.pdf, Web page accessed August 25, 2009.

Makhijani, A. and B. Smith, 2005b, "Costs and Risks of Depleted Uranium from a Proposed Enrichment Facility," *IEER Science for Democratic Action,* June 2005, http://www.ieer.org/reports/du/lesrpt.pdf, Web page accessed January 2, 2005.

Neary, Ben, 2005, "NM Leaders Strike Deal on Uranium Waste Plant," *The New Mexican*, June 4, 2005, http://www.santafenewmexican.com/, Web page accessed September 1, 2009.

NEI, 2005, "LES-AREVA Sign Pact for Deconversion Facility near National Enrichment Site," *Nuclear Energy Overview*, Nuclear Enterprise Institute newsletter, February 7, 2005.

NRC, 2003, *Application to the US NRC to Construct and Operate a Gas Centrifuge Enrichment Facility (National Enrichment Facility) near Eunice, New Mexico*, Docket No. 70-3103, December 12, 2003.

NRC, 2004a, *Application to the US NRC to Construct and Operate a Gas Centrifuge Enrichment Facility (American Centrifuge Plant) at the DOE Portsmouth, Ohio Site*, Docket 70-7003, August 23, 2004.

NRC, 2004, U.S. Nuclear Regulatory Commission Atomic Safety and Licensing Board, *In the Matter of \Louisiana Energy Services, L.P.*; Docket No. 70-3103-ML, July 19, 2004.

NRC, 2011, "Draft Environmental Impact Statement for the Proposed Fluorine Extraction Process and Depleted Uranium Deconversion Plant in Lea County, New Mexico," NUREG-2113, Dec. 2011.

Nuclear Fuel Cycle Monitor, 2008, Exchange Monitor Publications and Forums, "Senate Minority Leader and Kentucky Delegation Back Transfer of Tails to USEC," http://www.exchangemonitor.com/nuc_fuel.htm, Web page accessed August 25, 2009.

Platts, 2005a, "DOE Estimated Its Cost of Disposing of LES' Enrichment Tails," *Platt's Nuclear News Flashes,* Tuesday, April 12, 2005.

Platts, 2005b, "LES News," *Platt's Nuclear News Flashes*, May 27, 2005.

Platts, 2005c, "DOE to Transfer Depleted Uranium to BPA," *Platts Nuclear News Flashes*, July 6, 2005.

Platts, 2009, "International Isotopes has chosen Lea County, New Mexico, as the site for its uranium deconversion and fluorine extraction facility," Nuclear News Flashes, March 31, 2009.

World Nuclear Association, "Uranium Enrichment," Information Brief #28, updated July 2012. (http://www.world-nuclear.org/info/inf28.html) [WNA 2012]

K1.1-11.BIBLIOGRAPHY

DOE-NE, Science and Technology, 1999, *Final Plan for the Conversion of Depleted Uranium Hexafluoride: As Required by Public Law 105-204*, U.S. Department of Energy, July 1999, http://web.ead.anl.gov/uranium/pdf/finalplan.pdf, Web page accessed August 6, 2009.

Haire, M. J., and A. G. Croff, 2004, "Cost-Effectiveness of Utilizing Surplus Depleted Uranium (DU)," *Waste Management 2004 Symposium*, Tucson, Arizona, February 29–March 4, 2004, http://www.ornl.gov/~webworks/cppr/y2001/pres/119071.pdf, Web page accessed August 6, 2009.

Mullaly, Chris, IPA, 2009, "Best Practices for Executing Capital Projects – DUF_6 Lessons Learned," Independent Project Analysis, Inc., *Annual DOE Project Management Workshop, March 31–April 1, 2009, Hilton Alexandria Mark Center, Alexandria, Virginia*, www.2009doeworkshop.com/SpeakerPresentations/IPA_DOE%20presentation.pdf, Web page accessed August 6, 2009.

Nuclear Energy Agency and International Atomic Energy Agency, 2001, "Management of Depleted Uranium, Paris, France, Organization for Economic Cooperation and Development," ISBN 92-64-19525-4, 2001.

OECD, Nuclear Energy Agency and International Atomic Energy Agency, 1994, *The Economics of the Nuclear Fuel Cycle (1994),* pp. 11, 27, 37–38, 50, 77–80, http://www.nea.fr/html/ndd/reports/efc/, Web page accessed August 25, 2009

Module K1.2

Disposition: Geologic Disposal of Depleted Uranium Oxides

Page intentionally left blank

K1.2 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004	K1.2-All	**Version of AFC-CBR in which Module first appeared**: 2004 as Module K: Enrichment Plant DUF6 Tails Conversion (**Conversion and Disposal were combined**). In 2009 AFC-CBR Module K was separated into K1, K2, and K3 to differentiate between deconversion of enrichment plant tails (K1) and deconversion of uranium products (RU) arising from aqueous reprocessing (K2) and pyroprocessing (K3). In 2015 K1 was split into K1-1 (deconversion) and K1-2 (disposal)
	2015	K1.2-All	**Latest version of module in which new technical data was used to establish unit cost ranges**: 2015
		K1.2-All	New technical basis: [Schneider, E. and Williams, K.A.; ***DU and RU Disposal Costs***; Powerpoint presentation dated April 2015; 65 pages supplementary document 2017-CBR-SD]. It was used to establish and bound the unit cost ranges. Costs are expressed in 2012 constant dollars.
		K1.2-All	**New technical/cost data which has recently become available and will benefit next revision:** • The cost will be affected by the final regulations promulgated by the NRC for safe burial of a significant radon-generating uranium material. DOE and its GOCO deconversion contractors are negiating with private waste handlers Energy Solutions (Clive, Utah) and WCS (Andrews County, Texas) for shallow burial of the bulk packaged DU oxide. The trade press may include some cost information as well as any contract announcements by DOE-EM and its winning bidder.
		K1.2-All	**New technical/cost data which has recently become available and will benefit next revision:** • The cost will be affected by the final regulations promulgated by the NRC for safe burial of a significant radon-generating uranium material. DOE and its GOCO deconversion contractors are negiating with private waste handlers Energy Solutions (Clive, Utah) and WCS (Andrews County, Texas) for shallow burial of the bulk packaged DU oxide. The trade press may include some cost information as well as any contract announcements by DOE-EM and its winning bidder.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from

			year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

Page intentionally left blank

Module K1.2
Disposition: Geologic Disposal of Depleted Uranium Oxides

K1.2-MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY22 update.**
- **Nature of this FY21 Module update from previous AFC-CBRs: Escalation only.**
- Estimating Methodology for latest (201 AFC-CBR) technical update from which this FY22 update was escalated:
  - For disposal of DU oxide converted product: 2015 Parametric analysis of disposal technologies based on projected costs for other nuclear materials [viewgraph report by Schneider and Williams: 2015 supplementary document 2017-CBU-SD] This viewgraph report assumed year 2012$
  - It should be noted that Module K1-2 does not include deconversion of the DUF6 to a stable oxide. This activity is discussed in Module K1-1.

K1.2-1. BASIC INFORMATION

Context. During the late 1990s and into the 2000s, the US DOE studied disposition options for its 720,000 tonne UF_6 (as of 2007) inventory of depleted uranium (DU). DOE opted to deconvert its UF_6 and dispose of the resulting DU oxide, and plants were constructed at Paducah, KY and Portsmouth, OH to implement this strategy. The *December 2009 Advanced Fuel Cycle Cost Basis Report* (2009 CBR) reviewed the cost analysis literature supporting this project. Having collected data from the DOE project and other domestic and foreign DU deconversion and disposal efforts, the 2009 CBR arrived at a cost estimate for **combined deconversion and disposal operations**.

The 2012 AFC-CBR update had two parts. First, it reviewed industry events and cost data released subsequent to the 2009 AFC-CBR. Second, it reconsidered the data reported in the 2009 AFC-CBR in order **to break the combined cost estimate into separate estimates for deconversion and disposal**. Deconversion is an industrially-achieved process with large plants operating in the US and France. It is described in detail in Module K1.1. There is relatively little uncertainty associated with these deconversion costs. On the other hand, considerable disagreement exists between credible estimates of the cost of immobilizing and disposing large amounts of DU. (Much of the disagreement concerns which geologic disposal requirements and methodologies are adequate to protect health and the environment,) Separating the two processes (deconversion and disposal) will allow appropriate low, nominal and high cost estimates to be ascribed to each step. It will also permit modelers to consider post-deconversion strategies other than near-surface disposal at a LLW facility, the option being pursued by the US and presented here.

In this “stand alone” 2015 AFC-CBR the intent is to include all of the relevant information above; however, for purposes of clarity it has been decided to split this K1 Module into two parts: 1.) Module K1-1 which will consider only the deconversion of depleted UF6 to a stable oxide form, and 2) Module K1-2 which will explore the many possible options for permanent geologic disposal of the packaged depleted oxides. Unit cost probability distributions and a mean (expected value) in $/kgDU are reported in both Modules.

This Module K1-2 deals only with the latter (geologic disposal), and assumes that some stable oxide form exists in packages provided by the UF_6 deconversion contractor. The cost analysis here will include all additional treatment, additional repackaging if required, geologic emplacement, and subsequent monitoring costs required to safely dispose the material in an underground facility. This 2015 Module will also be informed by a recent 30+ page report (Schneider and Williams) taking a detailed look at several packaging and geologic disposal options. Many of these are options not considered in the 2009 AFC-CBR or the 2012 Update AFC-CBR. The chosen projected unit cost values, range, probability distribution, and expected value are all from this recent report.

Basic Information. Early in the DOE DUF6 disposition program it became apparent that the best route for permanent disposition of legacy DUF_6 is to convert it to a more stable and less-toxic chemical form, such as an oxide, and to isolate this form from the environment. In 2001, the U.S. nuclear and chemical industries were given the opportunity to propose and bid on the management, conversion, and disposition of the DOE-owned DUF_6 legacy material. Uranium Disposition Services, LLC (UDS), a consortium of three firms (Framatome-ANP, Duratek [now part of Energy Solutions, and Burns and Roe) was selected (DOE 2002) in 2002 to design and construct two DUF_6 to DU_3O_8 plants (one each at Paducah and Portsmouth [see Figure K1.2-4) and to contract for the disposition of the DU_3O_8 product in the same manner as is done for low-level waste (LLW). (Note that the conversion product is more accurately described as UOx [x~2.4 to 2.6], because there is some variation in stoichiometry.) The likely shallow burial resting place for this DU_3O_8 material, now to be packed in the old but washed-out UF_6 cylinders, was at that time designated to be Envirocare (a private firm now also part of the Energy Solutions consortium) in Clive, Utah, or the Nevada Test Site (NTS, a government site now renamed Nevada National Security Site) near Beatty, Nevada. Construction of the two DOE-owned conversion plants commenced on July 31, 2004 and they were completed in 2010, and are now operating. Early on it was determined that DOE's LLW facility at the Nevada Test Site (now the Nevada National Security Site) was the more economical and environmentally acceptable location for disposal of the DOE-legacy derived U_3O_8 (DOE 2004a and DOE 2004b). Now it appears that two commercial sites in the West are also possible disposal candidates. No material from the DOE Deconversion Plants, now operated by BWXT Conversion Services, has yet been shipped West and buried. The holdup is related to environmental, health, and regulatory issues as will be explained below.

K1.2-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

Disposal of the DU_3O_8 powder resulting from conversion has its own regulatory and procurement issues. UDS (now BWXT Conversion Services) or any other conversion plant owner/operator will need to contract with an LLW disposer, such as WCS, Envirocare or NTS, for shallow burial disposition. The converter must also appropriately package the powder to minimize water intrusion and allow safe transportation. Both purchased containers (such as supersacks or drums) or emptied, washed, and adapted DUF_6 cylinders were being considered for this purpose. The latter option has been deemed economically superior. The tipping fee for this material is likely to constitute a significant percentage of the unit cost ($/kgU) of the overall combined conversion/disposition life cycle. Because tipping may be charged on a $/volume basis, the conversion process will need to achieve an as reasonably high as possible bulk powder density that can accommodate transportation and tipping requirements. The volumes of material (DU_3O_8) projected from a likely U.S. uranium enrichment/conversion enterprise will likely require the opening of new or the major expansion of LLW near-surface disposal capacity (Module J). (Note: Costs of our new LLW capacity specifically for DU_3O_8 burial should be assigned to this step [Module K1 and not Module J]). The near surface disposal will allow the eventual recovery of this depleted-uranium material if the breeder reactor plutonium economy ever evolves in the distant future and DU would be needed for target fuel assemblies.

The regulation of the shallow geologic disposal as LLW of large amounts of bulk DU_3O_8 or other uranium forms remains an issue (NRC 2004). The very large inventory of this material and its

concentration in one area means that in the distant future (thousands of years), after the cylinders enclosing the insoluble DU_3O_8 corrode away, the burial area will be a large producer of radon gas from the uranium decay chain. This gas will easily diffuse through the dry soil cap. In order to prevent this occurrence, a deeper or more robust engineered capped burial site or non-corrodible containers will be needed. The NRC investigated the geologic disposal issue as part of the LES National Enrichment Facility licensing process, and a ruling was recently issued. In a March 2009 ruling (Fahys, Salt Lake Tribune 2009) the USNRC declared DU-materials from the commercial nuclear industry (NRC-licensees) to be Class-A LLW, thus they could be buried in a commercial LLW facility such as that owned and operated by Energy Solutions in Clive, Tooele County, Utah. To respond to stakeholder concerns, however, the Commission, based on Staff recommendations (NRC 2008) agreed to hold rulemaking hearings on this material (Federal Register 2009). This additional regulatory attention is warranted because of the large quantities of tails that are likely to be generated by NRC-licensed U.S. enrichment plants and the fact that DU's specific activity actually increases with time due to the long-term buildup of radioactive daughter products, including radon. (Figure K1.2-6 shows how these U-238 daughter products build in with time, just as they did with the original uranium ore.) DU compounds, such as DU_3O_8 are also in a very "dense" or concentrated form compared to most LLW, which is often equipment or substances with surface contamination only. It is possible that the NRC could rule that special packaging and/or burial precautions need to be taken such that radon release and dispersal does not pose an airborne hazard to local populations. Low permeability liners or clays might be required in conjunction with the normal shallow burial process. Others have suggested that disposal in deeper locations, such as old mines, might be appropriate. In any case, some retrievability should be maintained, since this DU material may become the nuclear fuel (U-238 transmuted to Pu-239) of the future when breeder reactors are deployed.

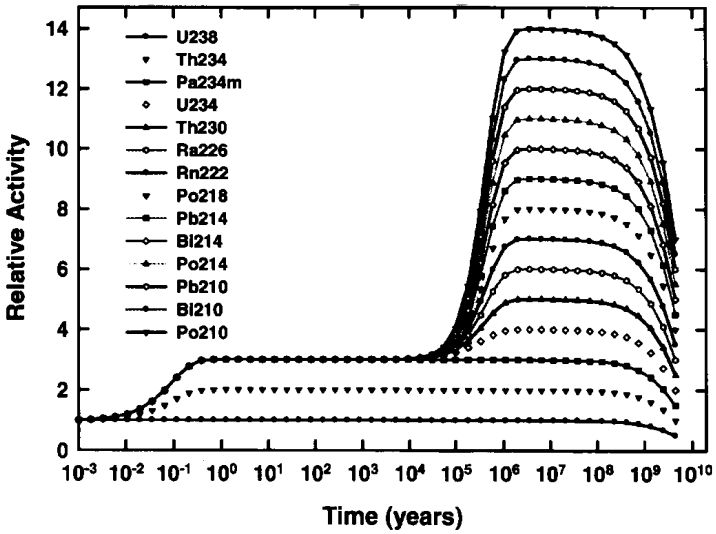

Figure K1.2-1. Buildup of decay products from depleted uranium as a function of time.

If stringent radon isolation and control is required, the unit disposition cost associated with more robust packaging and geologic disposal would be expected to rise significantly. NUREG/BR-0216 discusses the storage and disposal of LLW (NRC 2003).

K1.2-3. PICTURES AND DIAGRAMS

Figure K1.2-2 shows the generic schematic for the steps involved in the disposal of deconverted DUF_6. Some concepts may involved repackaging or processing the oxides (grouting). Transportation costs are not covered in this Module but are small compared to disposal costs. Because of the low specific activity of depleted uranium oxides, conventional commercial trucks and railcar transport can be used.

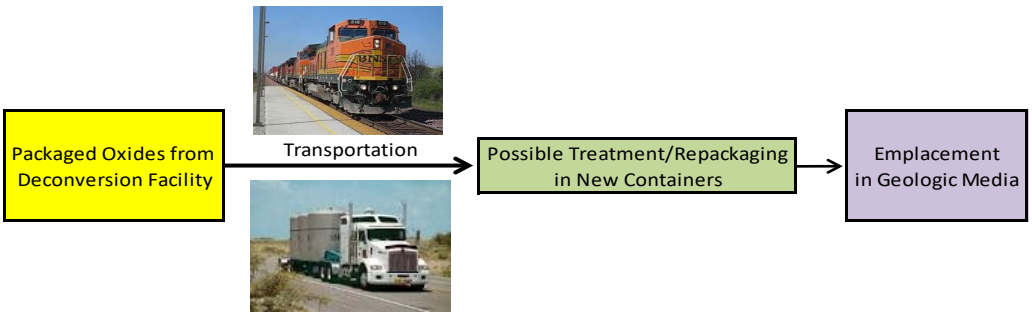

Figure K1.2-2. Generic Disposal Path for Oxides from Deconverted DUF_6.

K1.2-4. MODULE INTERFACES

Front-end interface. The cost of storage of DUF_6 at enrichment plant sites should be assigned to the enrichment plant operational costs. If DUF_6 conversion is to be located away from the enrichment plant site, the cost of DUF_6 transportation (in 14-ton cylinders) by rail or truck should be assigned to the DUF_6 to DU_3O_8 conversion facility. Experience shows that these transportation costs are relatively small.

Back-end interface. The inherent geology of the disposal medium may be an issue, and performance analyses may be required to certify particular locations and geologies. If stringent radon isolation and control is required, the unit disposition cost associated with more robust packaging and geologic disposal would be expected to rise significantly. NUREG/BR-0216 discusses the storage and disposal of LLW (NRC 2003). These issues are discussed in detail in a recent report (Schneider and Williams).

K1.2-5. SCALING CONSIDERATIONS

Since disposal methods require relatively little process chemistry or in-plant processing, process scalability (i.e. plant cost as a function of capacity) is not really an issue. Disposal costs are generally assessed on a cost per volume basis, for this reason powder bulk density, packaging efficiency, and emplacement efficiency will be major cost factors which will drive the cost per unut mass of DU disposed.

K1.2-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The 2009 and 2012 CBRs reported many data points for deconversion, disposal and combined deconversion and disposal costs. These are summarized in Table K1.2-1. Note that Table K1.2-1 includes cost estimates for deconversion as well as disposal; the full table was carried over from the 2012 CBR because it includes several estimates that combine deconversion and disposal costs. Also included in the table are cost estimates identified by Louisiana Energy Services while it was preparing the license application for its New Mexico facility. LES used this data to support of its argument that setting aside $5.5 ($7.04/kg U in 2012) per kg of DU it generated was sufficient to ensure that funds would exist to cover its disposition[h]. The new data presented in Module K1 of the 2012 AFC-CBR Update concludes the table.

h. In the event, LES was required to post a bond of $7.15/kg of DU (2005 dollars).

Table K1.2-1. Summary of deconversion and disposal costs and estimates.

Facility or Author[1]	Scope	Reported Cost [$/kgU]	Basis Year	CPI Factor	**Unit Cost [2012 $/kgU]**	Comments & 2009 CBR Reference
Paducah	Both	3	2004	1.224	**3.67**	DOE 2007; HF credit included
(LLNL Study)	Both	5.38	2004	1.224	**6.59**	Elayat 1997 (LLNL Study)
(LES Study)	Both	5.5	2002	1.280	**7.04**	NRC 2003
N/A	Both	7.15	2005	1.189	**8.50**	Neary 2005; Bond posted to state of New Mexico to provide surety of disposal funds
(IEER Study)	Both	30	2005	1.189	**35.66**	Makhijani 2005a; IEER position on appropriate value of bond
NTS	Disposal	11.6	2003	1.248	**14.47**	DOE 2005; Thorium disposal. Costs in $/kg Th.
(Diehl Study)	Disposal	110	2007	1.120	**123.21**	Diehl 2007; Discounted as unrealistic - see 2009 CBR
Data quoted in K1-4 review						
(LLNL Study)	Deconversion	2.64	2002	1.280	**3.38**	HF Sale
(LLNL Study)	Deconversion	3.39	2002	1.280	**4.34**	HF Neutralization
(LLNL Study)	Disposal	1.71	2002	1.280	**2.19**	Trench Disposal
(LLNL Study)	Disposal	2.42	2002	1.280	**3.10**	Vault Disposal
(Claiborne Energy Center Study)	Deconversion	4.93	2002	1.280	**6.31**	Based on quote by Cogema in 1993 for services at Tricastin
(Claiborne Energy Center Study)	Disposal	1.81	2002	1.280	**2.32**	From estimate provided by Urenco in 1993
Data added in this update						
INIS	Deconversion	14.47	2012	1.000	**14.47**	Smaller (Phase 1) plant
INIS	Deconversion	7.35	2012	1.000	**7.35**	Larger (Phase 1&2) Plant
Paducah	Both	5.33	2012	1.000	**5.33**	If a plant identical to Paducah was privately built & operated
INIS	Disposal	1.41	2012	1.000	**1.41**	Low estimate
INIS	Disposal	3.83	2012	1.000	**3.83**	High estimate
1. (Study) = based on a generic plant and process, not tied to a specific facility						

Antinuclear groups such as Institute for Energy and Environmental Research (Makhijani and Smith 2005a) suggest that even a bond of $8.5 per KgDU is too low a value, and that values as high as $30/kgU should be used for the bond (Makhijani and Smith 2005b). Such a high value would imply that shallow burial of the DU_3O_8 would not be allowable because of radon considerations and that deep burial in a mine or geologic repository would be required. Hopefully, all nuclear fuel cycle nations with enrichment plants will ultimately agree that DUF_6 conversion/disposition is environmentally necessary and will add the needed DUF_6 conversion/disposal capacity, which will eventually level the playing field for enrichment pricing. A new path for DUF_6 disposition is now being pursued (i.e., re-enrichment of the tails to produce natural assay feed). Rising uranium ore and conversion prices have convinced the Bonneville Power Administration that such a scheme is economic (Platts 2005c). The economics of tails re-enrichment will be discussed in more detail in Module C and is also the subject of ongoing study by DOE, as indicated by recent issuance of a uranium management plan (DOE 2008).

Another very useful "actual" cost number relevant to DU disposition is that for the packaging, transportation, and disposal of 7 million pounds (1.29 million kg Th) of U.S. government surplus thorium nitrate pentahydrate [$Th(NO_3)_4*5H_2O$] powder. This material has radiological and morphological properties very similar to natural or depleted uranium and was formerly warehoused at the Department of

Defense (DOD) depots in Curtis Bay, Maryland and Hammond, Indiana. In the period 2004–2005 this material was repackaged, transported, and disposed by geologic shallow burial at the DOE Nevada Test Site. (The Nevada Test Site is also likely to receive DU_3O_8.) The cost for this entire effort was $15M in 2003$ or a unit cost of $11.6/kgTh. In 2008 dollars this is $13.5/kgTh. Documentation of this activity can be found in Hermes 2001, Hermes 2003, Hermes 2006, and DOD 2005. The disposition rate (MT/yr) for this material is over an order of magnitude smaller than that projected for DU. Therefore, it is not surprising that a somewhat higher unit cost for disposing of thorium was experienced as compared to the projected unit cost of disposition of DU materials. Further discussion of thorium can be found in Modules A2 and D1-8 of this report.

K1.2-7. DATA LIMITATIONS

The following consideration is relevant to depleted-uranium materials in the fuel cycle:

- An unfavorable ruling from the NRC or an NRC ruling requiring stringent radon mitigation measures on shallow burial of DU_3O_8 at commercial LWR disposal sites, such as Envirocare, could significantly impact the unit cost, because a more expensive burial solution would be needed. Such a ruling might force burial at a non-NRC regulated site such as DOE's Nevada Test Site (Makhijani and Smith 2005b).[i] Even at a government site, such as Nevada Test Site, some radon amelioration measures are likely to be required. As mentioned earlier, NTS or commercial sites such as WCS in Texas and Envirocare (Energy Solutions) in Utah are the preferred disposal options. A new (Aug 2015) report (Schneider and Williams) reviews other options.

In general, the DUF_6 conversion/disposal step of the fuel cycle can be placed in the viable-commercial category of technology readiness.

K1.2-8. COST SUMMARIES

Module K1-1 presented cost data for a private deconversion facility to be built by INIS. There was also some data found which considered disposal costs for their deconverted product. INIS plans to dispose of its DU_3O_8 at a LLW facility. Ref. [International Isotopes Fluorine Products, 2009] identified the Energy Solutions facility in Utah and Waste Control Specialists in Texas as suitable facilities. Low and high range disposal cost estimates are given in [NRC, 2011] in 2009 dollars for the Phase 1&2 option; Table K1.2-2 converts these estimates to 2012 dollars and divides by the Phase 1&2 capacity to arrive at unit disposal costs.

Table K1.2-2. INIS low and high estimates of DU and other waste disposal.[1]

	Low Estimate		High Estimate	
	M$(2012)/yr	$/kg U	M$(2012)/yr	$/kg U
DU3O8	8.59	1.30	24.16	3.65
Other wastes*	0.78	0.12	1.23	0.19
Total Disposal Cost	9.37	**1.41**	25.40	**3.83**
1. Process and miscellaneous LLW, RCRA and sanitary waste associated with DU operations				

Based on the above and other cost studies, the following cost parameters were selected for the 2012 update to the AFC-CBD:

- The **mode** estimate, $4/kg U, is closest to the high-end forecast provided by INIS. It also lies above estimates made by Urenco and LLNL. It assumes that shallow trench burial, or concretization followed by vault burial, will remain feasible even as large amounts of DU reach LLW facilities. But it considers that scale effects may be small or even negative: i.e., disposal of hundreds of thousands of

i. Personal communication from D. W. Lee, Oak Ridge National Laboratory.

tonnes of DU at a single site may increase unit costs by necessitating deeper burial and/or more extensive and costly vault structures to mitigate radon release or migration into soil. Also, disposal costs have risen over time (see Modules J, K2 and K3) and it is conservative to build in an assumption that they will keep doing so.

- The **low cost** estimate, $2/kg U, compares with the most favorable of the estimates in Table K1.2-3. It assumes that scale effects will be neutral or positive, that shallow trench burial will remain feasible, and that disposal cost escalation will not play a significant role.
- The **high cost** estimate, $22/kg U, is informed by two entries in Table K1.2-3: the $14.5/kg Th cost to DOD of disposing of thorium holdings at the Nevada Test Site and the IEER estimate of $35.7/kg U for deconversion/disposal if deep burial is required. The thorium data point reflects actual, realized costs; while the amount of Th disposed was not large, significant scale benefits may not be present. The IEER figure assumes that the radon source arising from shallow burial DU will be judged unacceptably high so that deep burial will become necessary. $22/kg U is the average of the DOD and IEER figures (having subtracted the nominal deconversion cost from the IEER number), so the high estimate gives equal weight to deep burial and immobilization/disposition in a specialized facility at NTS as cost drivers.

Table K1.2-3. "What-it-takes" (WIT) Table from 2012 AFC-CBR Update (2012$).

	Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
Deconversion	$6/ kg U	$4/ kg U	$8/ kg U	$6/ kg U
Disposal	**$4/ kg U**	**$2/ kg U**	**$22/ kg U**	**$4/ kg U**
Total (2012 values)	$10/kg U	$6/ kgU	$30/ kgU	$10/ kg U
	2009 CBR Values for combined deconversion and disposal:			
Both	$11/kg U	$6/kg U in UF_6	$50/kg U in UF_6	$11/kg U in UF_6

We now report the summarized results (in 2012$) of the most recent August 2015 study (See Schneider and Williams presentation in supplementary documents) which addresses disposal only and considers multiple geologic disposal methods.

The **low-cost** case reflects the nominal cost of shallow vault DU disposal reported in Module K1 of the earlier AFC CBRs. This cost estimate was itself a synthesis of several other analyses, and additional calculations for two vault facilities presented in the Schneider-Williams study confirm the value of $4/kg DU. Note that the estimated cost of disposal of DU in shallow boreholes (Case 4a in Schneider and Williams) lies near this value as well. This is unsurprising since the depth and amount of excavation associated with shallow boreholes are similar to those of LLW vaults.

In a substantial change from the 2009 and 2012 AFC CBRs, both the most likely and high cost cases assume that measures beyond shallow vault disposal will ultimately be needed to disposition a growing US DU inventory. While shallow disposal of hundreds of thousands of tonnes of DU may ultimately be realized at WCS, Energy Solutions' Clive facility, NNSS or elsewhere, both co-disposal in a DGR (Case 3a in study) and disposition in intermediate-depth boreholes (Case 4b in study) are considered to be viable with a high degree of confidence even for very large amounts of DU. Hence these are selected to represent the **mode or most likely case**, which is assigned a value of $12/kg DU. Note that DGR case 3a assumes that the excavated footprint of the repository does not need to be expanded in order to co-dispose of DU.

Finally, the **high-cost** case takes the pessimistic view that the DU must be disposed in substantially the same manner as HLW. The two representative cases are now 3b (DGR disposal with additional excavation required to accommodate a larger footprint) and 4c (deep borehole disposal). A cost of $40/kg U is selected, with only one significant figure preserved to reflect the uncertainty associated with this

outcome. Table K1.2-4 summarizes the Schneider-Williams results, following the 'what-it-takes' table format of the AFC-CBR**. This new cost analysis was performed in 2012$ to allow consistency with the 2012 CBR, so escalation from 2012 dollars to 2017 dollars was necessary for the table and figure below**. For this 2017 Module K1-2 version, further escalation (a factor of 1.09) from 2012 to 2017 is assumed, and is based on the escalation indices in the "Escalation Considerations" chapter in the main 2017 AFC-CBR.

Table K1.2-4 Unit Disposal Costs for Depleted Uranium Oxides in $/kgDU (2020$)

Low Cost	Mode Cost	Mean Cost	High Cost
$4.5/kg DU	$13.6/kg DU	$21.2/kg DU	$45.3/kg DU
Large quantities of DU can be disposed as LLW in shallow trenches (Case 1) or shallow boreholes (Case 4a)	DU must be disposed in intermediate-depth boreholes (Case 4b) or co-disposed in a DGR (Case 3a)	Calculated	DU must be disposed in deep boreholes (Case 4c) or co-disposed in a DGR with substantial additional excavation required (Case 3b)

Figure K1.2-3 shows the resulting probability distribution and associated calculated mean or "expected value".

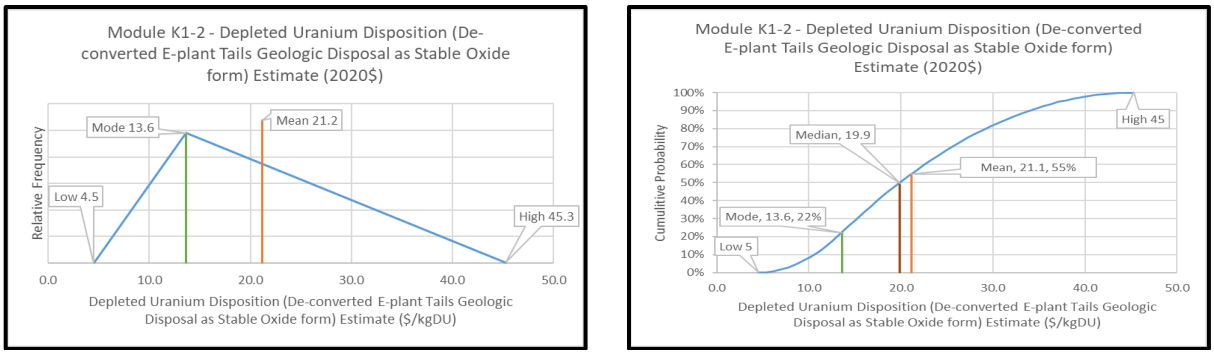

Figure K1.2-3. Depleted U conversion and disposition estimated unit cost frequency distribution.

K1.2-9. SENSITIVITY AND UNCERTAINTY ANALYSES

Not presently available.

K1.2-10.REFERENCES

Diehl, Peter, 2007, *Re-enrichment of West European Depleted Uranium Tails in Russia,* Ecodefense Russia, June 2007, http://www.wise-uranium.org/edumu.html, Web page accessed August 25, 2009.

DOD 2005; Department of Defense Revolving Funds – Justification/Overview: FY 2006/2007 President's Budget Estimates; February 2005.

DOE, 2004a, *Record of Decision for Construction and Operation of a Depleted Uranium Hexafluoride Conversion Facility at the Paducah, Kentucky Site*, U.S. Department of Energy, July 20, 2004, http://web.ead.anl.gov/uranium/pdf/PadROD.pdf, Web page accessed August 25, 2009.

DOE, 2004b, *Record of Decision for Construction and Operation of a Depleted Uranium Hexafluoride Conversion Facility at the Portsmouth, Ohio Site,* U.S. Department of Energy, July 20, 2004, http://web.ead.anl.gov/uranium/pdf/PortROD.pdf, Web page accessed August 25, 2009.

DOE, 2005, *Site Specific Environmental Impact Statement for Depleted Uranium Conversion Facility to be Constructed at Paducah, Kentucky*, DOE/EIS-0359, U.S. Department of Energy, http://web.ead.anl.gov/uranium/pdf/PAD-Cover.pdf, Web page accessed August 25, 2009.

DOE, 2007, *Draft Supplement Analysis for Location(s) to Dispose of Deplete Uranium Oxide Conversion Product Generated from DOE's Inventory of Depleted Uranium Hexafluoride*, DOE/EIS-0359-SA1 and DOE/EIS-0360-SA1, U.S. Department of Energy, March 2007.

DOE, 2008, *Excess Uranium Inventory Management Plan*, U.S. Department of Energy, December 16, 2008

Elayat, H., J. Zoller, Lisa Szytel, 1977, *Cost Analysis Report for the Long-Term Management of Depleted Uranium Hexafluoride,* UCRL-AR-127650, Lawrence Livermore National Laboratory, May 1977, http://web.ead.anl.gov/uranium/documents/paddeis/index.cfm, Web page accessed August 25, 2009.

Fahys, Judy, Salt Lake Tribune, 2009, "Ruling Clears Way for Store Depleted Uranium," March 18, 2009.

Hermes, et al. 2001, "Thorium Nitrate Material Inventory Definition Report," Oak Ridge National Laboratory, ORNL/TM-2000/163, June 2001 (Official Use Only).

Hermes, et al 2003, "Thorium Nitrate Stockpile – From Here to Eternity," Paper presented to the Waste Mnagement '03 Conference; Tucson, Arizona; February 23–27, 2003.

Hermes, 2006, "Removing the Source Term – Thorium Nitrate Disposal at the Nevada Test Site"; W.H. Hermes; Oak Ridge National Laboratory; Paper presented to the Health Physics Society 2007 Midyear Topical meeting, Knoxville, Tennessee, January 21–24, 2006.

International Isotopes Fluorine Products, Inc., "Fluorine Extraction Process & Depleted Uranium De-conversion Plant Environmental Report," technical report ER-IFP-001 Rev A, December 2009.

Makhijani, A. and B. Smith, 2005a, "Costs and Risks of Management and Disposal of Depleted Uranium from the National Enrichment Facility Proposed to be Built in Lea County New Mexico by LES," *Institute for Energy and Environmental Research*, version for public release redacted March 20, 2007, http://www.ieer.org/reports/du/LESrptfeb05.pdf, Web page accessed August 25, 2009.

Makhijani, A. and B. Smith, 2005b, "Costs and Risks of Depleted Uranium from a Proposed Enrichment Facility," *IEER Science for Democratic Action,* June 2005, http://www.ieer.org/reports/du/lesrpt.pdf, Web page accessed January 2, 2005.

Neary, Ben, 2005, "NM Leaders Strike Deal on Uranium Waste Plant," *The New Mexican*, June 4, 2005, http://www.santafenewmexican.com/, Web page accessed September 1, 2009.

NRC, 2003, *Application to the US NRC to Construct and Operate a Gas Centrifuge Enrichment Facility (National Enrichment Facility) near Eunice, New Mexico*, Docket No. 70-3103, December 12, 2003.

NRC, 2004, U.S. Nuclear Regulatory Commission Atomic Safety and Licensing Board, *In the Matter of Louisiana Energy Services, L.P.*; Docket No. 70-3103-ML, July 19, 2004.

NRC 2008, "Response to Commission Order CLI-05-20 Regarding Depleted Uranium," SECY-08-0147, October 7, 2008.

NRC-2009-0257, "Announcement Notice of Public Workshop on a Potential Rulemaking for Safe Disposal of Unique Waste Streams Including Significant Quantities of Depleted Uranium," *Federal Register*, U.S. Nuclear Regulatory Commission, June 24, 2009.

NRC, 2011, "Draft Environmental Impact Statement for the Proposed Fluorine Extraction Process and Depleted Uranium Deconversion Plant in Lea County, New Mexico," NUREG-2113, Dec. 2011.

Platts, 2005c, "DOE to Transfer Depleted Uranium to BPA," *Platts Nuclear News Flashes*, July 6, 2005.

Schneider, E. and Williams K., *Depleted Uranium Disposal Options and Costs,* unpublished viewgraph report, Idaho National Laboratory, August 2015. (Supplementary document 2017-CBR-SD)

K1.2-11. BIBLIOGRAPHY

Bunn, M., et al., 2003, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Cambridge, Massachusetts, Project on Managing the Atom, Harvard University, DE, http://belfercenter.ksg.harvard.edu/publication/2089/economics_of_reprocessing_vs_direct_disposal_of_spent_nuclear_fuel.html, Web page accessed August 25, 2009.

DOE, 2001, *DUF_6 Management Information Network*, U.S. Department of Energy, www.ead.anl.gov/uranium.html, Web page accessed August 25, 2009.

DOE-NE, Science and Technology, 1999, *Final Plan for the Conversion of Depleted Uranium Hexafluoride: As Required by Public Law 105-204*, U.S. Department of Energy, July 1999, http://web.ead.anl.gov/uranium/pdf/finalplan.pdf, Web page accessed August 6, 2009.

Haire, M. J., and A. G. Croff, 2004, "Cost-Effectiveness of Utilizing Surplus Depleted Uranium (DU)," *Waste Management 2004 Symposium*, Tucson, Arizona, February 29–March 4, 2004, http://www.ornl.gov/~webworks/cppr/y2001/pres/119071.pdf, Web page accessed August 6, 2009.

Nuclear Energy Agency and International Atomic Energy Agency, 2001, "Management of Depleted Uranium, Paris, France, Organization for Economic Cooperation and Development," ISBN 92-64-19525-4, 2001.

OECD, Nuclear Energy Agency and International Atomic Energy Agency, 1994, *The Economics of the Nuclear Fuel Cycle (1994),* pp. 11, 27, 37–38, 50, 77–80, http://www.nea.fr/html/ndd/reports/efc/, Web page accessed August 25, 2009.