K MODULES

Excess Uranium Conversion and Disposal

Module K1-1

Deconversion of Depleted UF6 to Depleted Uranium Oxides

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 for 2017 Update:** FY 2017

- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only from 2012 values.

- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:**

  o For DUF_6 to DUOx deconversion: Actual early operational data for DOE facilities and projected pricing data for private NRC-licensed facility.

  o 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-RH. REVISION HISTORY

- **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)

- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2012 for deconversion

- **New technical/cost data which has recently become available and will benefit next revision:**

  o Further analysis by USNRC to establish price for US Government (DOE) deconversion of tails from private US Enrichment plants

  o 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.

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

For this 2015 AFC-CBD document, which is not an update but rather a complete document with all of the background technology and facility information, it was decided to separate Module K-1 into two parts, with Module K-1-1 covering the DUF6 to depleted uranium oxide conversion process and Module K1-2 covering the oxide packaging and oxide geologic disposal. This Module K-1 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). 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 K-2.) 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 K1-2 and K1-4). 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).
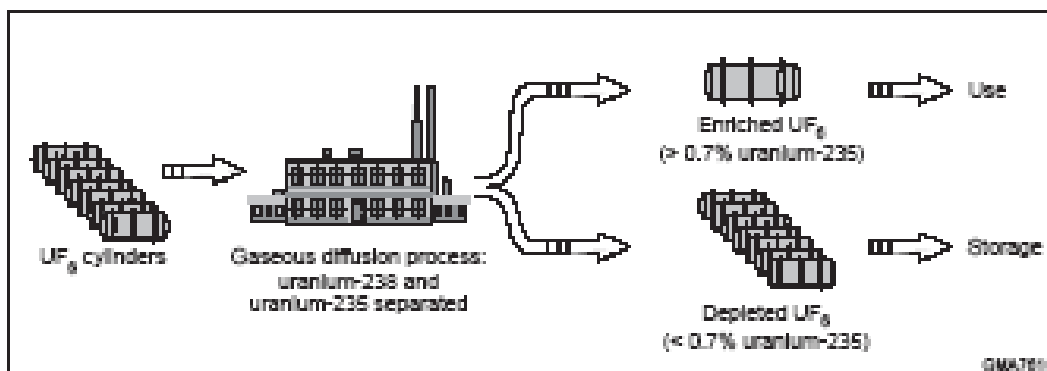

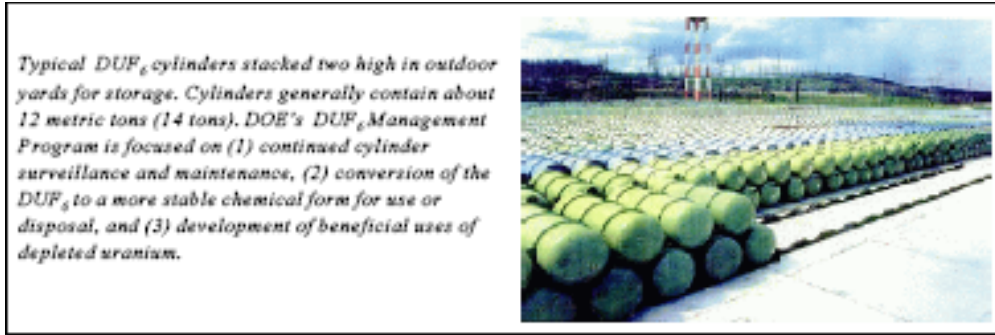Figure K1-1-1. DUF_6 is the by-product of uranium enrichment (DOE 2001).

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 K1-3 shows how the U-235 assay of the depleted UF_6 inventory is distributed.
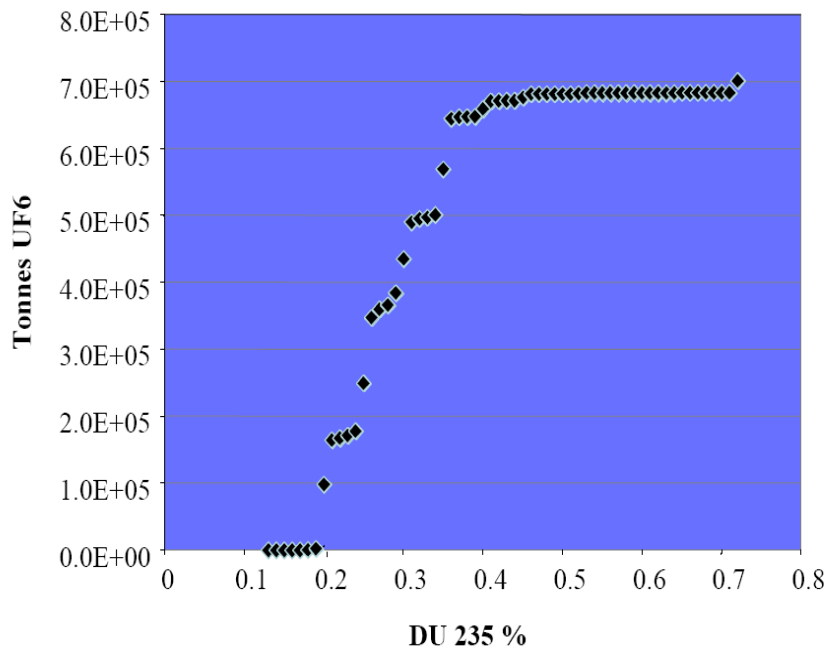

Figure K1-1-3. Cumulative distribution of DUF_6 metric tonnage versus U-235 assay.

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 K1-4] 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 UO_x [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]

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[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.
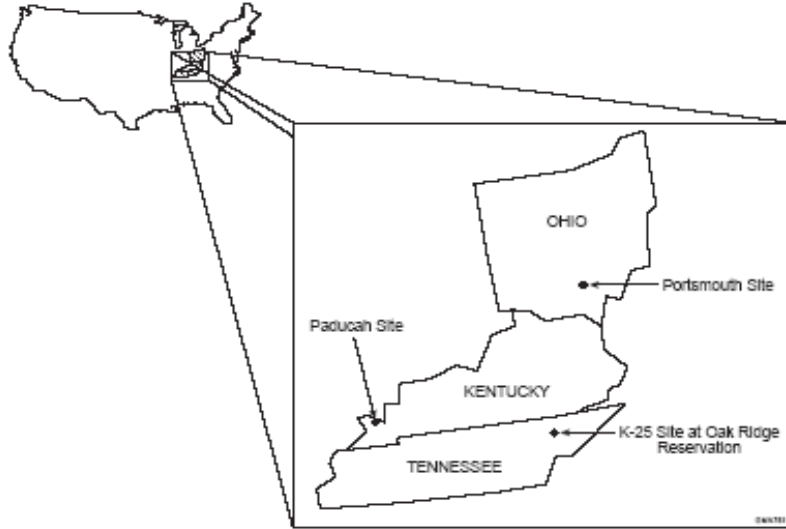
Figure K1-1-4. Source locations of U.S. DUF$_6$ stockpile (all DUF$_6$ now at Paducah and Portsmouth) (DOE 2001).

Currently these two deonversion 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 DUF$_6$ 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) $\rightarrow$ UO_2F_2(s) + 4HF (v)

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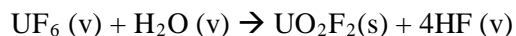
where

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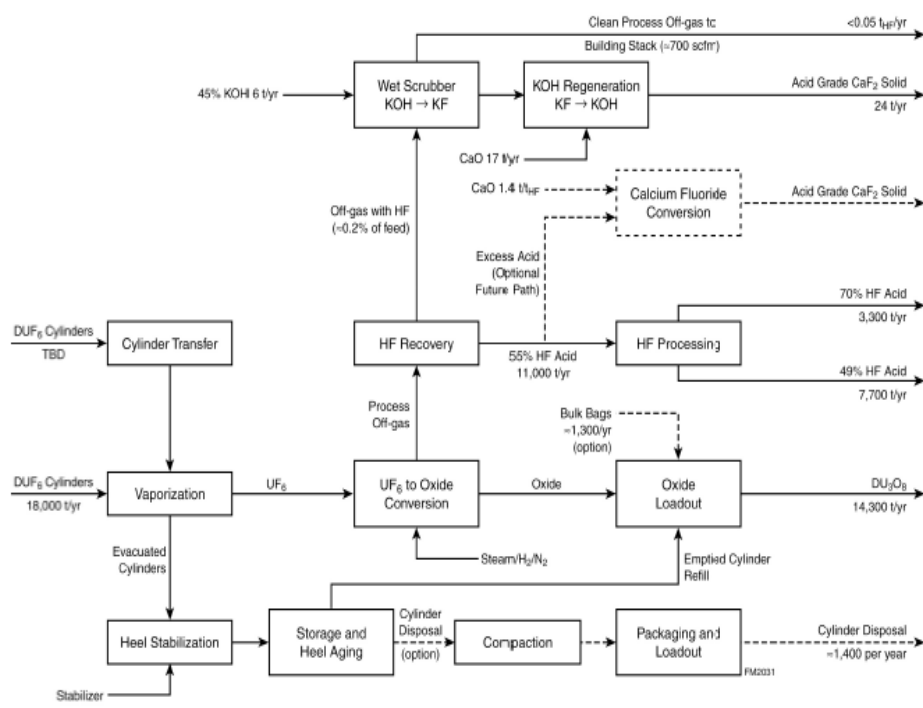
Figure K1-1-5. DUF_6 to DU_3O_8 conversion process (DOE 2007).

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 ($\approx$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 K-1-2 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 K-1-2-1 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.

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[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 $3.34/kgDUF_6$ 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.

Table K1-3. 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 $11/kgU selected unit cost value should reflect such conversion facility cost escalation and likely prolonged regulatory and contracting difficulties with DU$_3$O$_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.

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[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 **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.

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 2017$ 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 $428M 5-year (2011-2015) contract cost by the approximately 100,000 MTDUF6 they have already processed to date. The excalation factor from 2012$ to 2017$ is only 1.09, so the rounded escalated 2017$ unit costs are just slightly above the 2012 values when rounded to the nearest tenth of adollar. 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 $6.5/kgU in 2017$. For the 2017 Table and figure below an escalation factor of 1.09 (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 (2017$).

	Reference Cost(s) Based on Reference Capacity	Low Cost 2017$	Mode Cost 2017$	Mean Cost 2017$	High Cost 2017$
Deconversion only (without oxide geologic disposal)	$6/ kg U in 2012$	$4.4/ kg U	$6.5/ kg U	$6.5/ kg U	$8.7/ kg U

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[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.

Module K-1-1
Deconversion of DUF6 to DU oxide

For this case mode = mean = 6.5

Relative
Frequency

Low   High
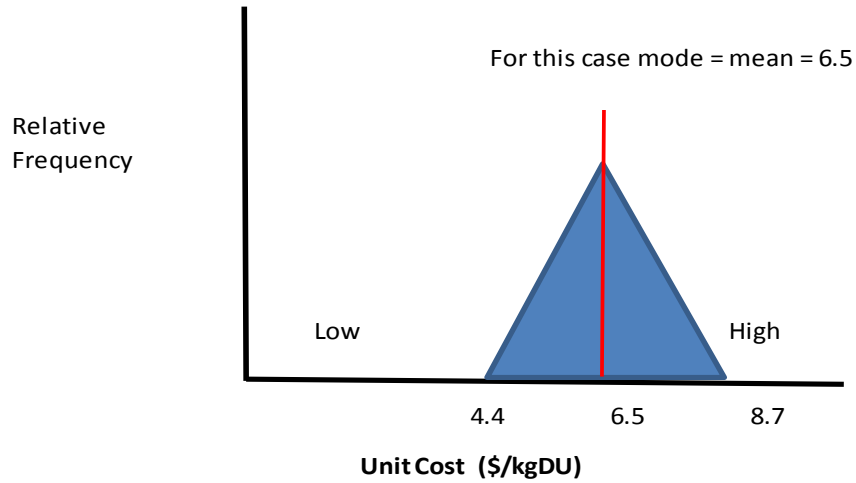
4.4   6.5   8.7

Unit Cost ($/kgDU)

Figure K1-6. Depleted U deconversion estimated unit cost frequency distribution (2017$).

K1-1-9. SENSITIVITY AND UNCERTAINTY ANALYSES

Not presently available.

K1-1-10.   REFERENCES

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Module K1-2

Disposition: Geologic Disposal of Depleted Uranium Oxides

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 for 2017 Update**: FY 2017**
- Nature of this 2017 Module update from previous AFC-CBRs**: escalation only (from 2012$)**
- Estimating Methodology for latest (201 AFC-CBR) technical update from which this 2017 update was escalated:
  - For disposal of DU oxide converted product: 2015 Parametric analysis of disposal technologies based on projected costs for other nuclear materials [viewgraph report by Schneider and Williams: 2015 supplementary document 2017-CBU-SD] This viewgraph report assumed year 2012$
  - 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-RH   REVISION HISTORY

- **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)
- **Latest version of module in which new technical data was used to establish unit cost ranges**: 2015
- 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.
- **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.

K1.2-1. 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 K-1 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 K1-4) 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 K1-6 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.
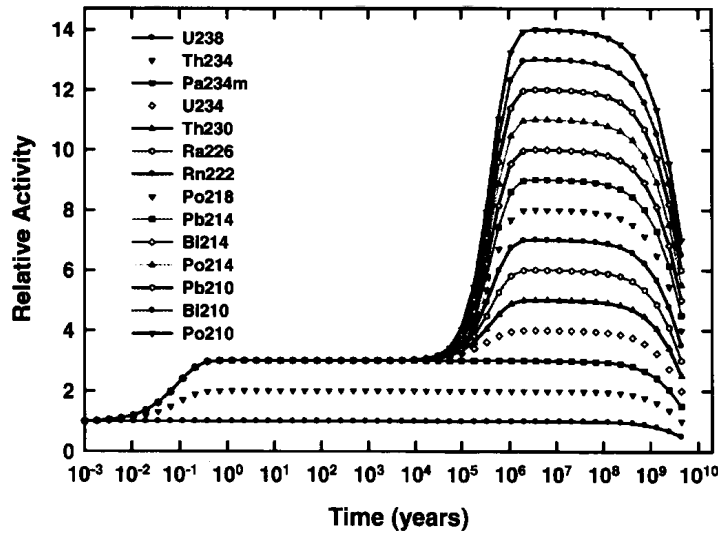
Figure K1-2-1. Buildup of decay products from depleted uranium as a function of time.

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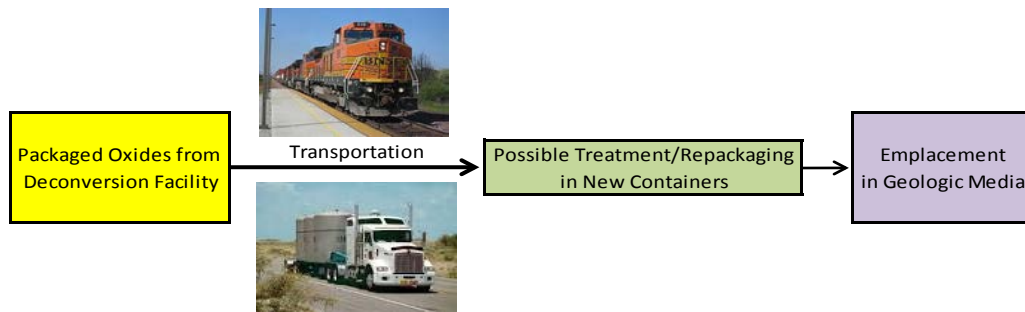
Figure K1-2-2   Generic Disposal Path for Oxides from Deconverted DUF_6.

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 K-1-2-1 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 K-1 of the 2012 AFC-CBR Update concludes the table.

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						

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

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.

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

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 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 $/kgDU (2017$)

Low Cost	Mode Cost	Mean Cost	High Cost
$4.4/kg DU	$14.1/kg DU	$21.4/kg DU	$45.8/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".

Module K-1-2
Geologic Disposal of Deconverted Oxides
(Yr 2017$)
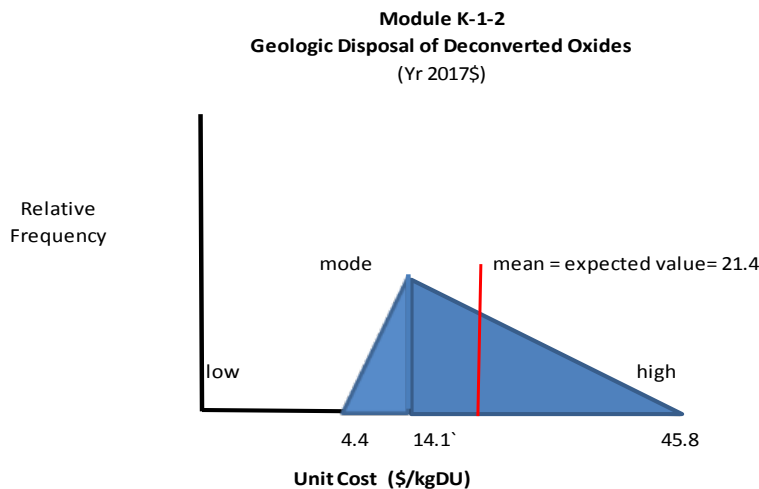
K1.2-9. Figure K1-3. Depleted U conversion and disposition estimated unit cost frequency distribution.

K1.2-10. SENSITIVITY AND UNCERTAINTY ANALYSES

Not presently available.

K1.2-11.REFERENCES

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Module K2

Aqueously Reprocessed Uranium Conversion, Disposition, and Possible Recycle

Module K-2
Aqueously Reprocessed Uranium Conversion, Disposition, and Possible Recycle

K2.MD   SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest technical updates from which this 2017 update was escalated:**
  o Conversion and **storage costs** were based on literature survey and some adjustments made in 2009 AFC-CBR. Moxable UO2 preparation costs were revisited in 2012 AFC-CBR.
  o Geologic disposal costs were based on E. Schneider and K. Williams' 2015 analysis cited in the K1 module. **A view graph report of this analysis is a supplementary document to this 2017 AFC-CBR. (2017-CBR-SD-7)**

K2.RH   REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2006 as Module K2.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2009 and 2012 for most REPU chemical conversion and storage steps, 2015 for oxide geologic disposal step, 2012 for REPU to MOX diluent process.
- **New technical/cost data which has recently become available and will benefit next revision:**
  o Russia occasionally publishes reports on their reprocessed uranium recycling program. New ones might be available.
  o Canada and China are still considering uranium recycling despite the fact that natural U is presently very cheap due to depressed market.

K2-1.   BASIC INFORMATION

2009 AFC-CBD Basic Information. For light-water reactor (LWR) fuel cycles and some fast reactor fuel cycles, uranium is the largest resulting constituent of the irradiated spent fuel mass. If it is separated during reprocessing of spent fuel, it is known as "reprocessed uranium" (REPU or sometimes RU). For LWR operating on enriched UOX, only a small fraction of the total initial uranium radioisotopes is fissioned or transmuted to other actinides. After discharge from the reactor, typically over 93% of the heavy metal mass (not including zircalloy cladding or fuel assembly structures) is uranium. In the spent fuel pools of U.S. reactors, there is already over 58,000 MTU (year 2006) of this material, which might be ultimately recovered as reprocessed uranium during future reprocessing operations. At first glance it would seem that this reprocessed uranium material could be economically recovered during reprocessing and reused in the fuel cycle. Doing so could reduce requirements for uranium ore and conversion and enrichment services. Realistically, however, there are several factors that affect the "recyclability," hence the economics, of this reprocessed uranium and its ultimate path through the fuel cycle. These are:

- The initial U-235 assay of the fuel before irradiation (this is one of the variables that will determine the post-irradiation U-235 assay and the concentrations of other uranium isotopes, such as U-236). Erich Schneider has developed algorithms that allow calculation of the U-235 and U-236 content

from the initial U-235 value and the fuel burnup for both PWR and BWR UOX fuel (Schneider et al. 2007). These calculations are based on runs made with neutronics/depletion codes.

- The burnup level of the spent fuel, which also determines the fractions of the various isotopes of uranium in the irradiated fuel. (The higher the burnup, the smaller the ratio of the post irradiation U-235 content to the preirradiation U-235 content.) For example, pressurized water reactor fuel that starts out at 3.5–4.5% U-235 prior to irradiation could end up with 0.5–1.3% U-235 depending on initial assay and burnup. Because of these low postirradiation U-235 assays, any reprocessed uranium would need to be converted to UF_6 and re-enriched before being fabricated into "recycle" LWR UOX fuel for LWRs. (Reprocessed uranium might be more directly used in CANDU reactors. Del Cul et al. discussed this concept in a paper and report and it is presented in a later section below (Del Cul 2007 and 2009). Platt's 2002 article also discusses some of the technical issues associated with REPU use as LWR fuel burnup increases (Platts 2002).

- The initial U-235 assay and the burnup also determine the amounts of the undesirable isotopes U-232 and U-236 that are formed. Short-lived U-232 has radiologically potent decay daughters such as thallium-208, which complicate reprocessed uranium handling, and U-236 is a neutron poison (absorber), which adversely affects the performance of any new UOX fuel that is produced from reprocessed uranium. The higher the initial U-235 assay and burnup, the more of these undesirable, non-natural uranium radioisotopes are produced.

- The nature and chemistry of the reprocessing scheme (the associated "decontamination factors") determine the amounts of non-uranium impurities such as fission products (i.e., technicium) and higher actinides, such as plutonium and neptunium, carried over into the reprocessed uranium stream. Aqueous processes, such as uranium extraction (UREX) and plutonium-uranium extraction (PUREX), have higher decontamination factors for separating uranium from fission products and higher actinides. The very low quantities of non-uranium impurities mean that any further handling of the reprocessed uranium stream can be in "contact-handling" facilities, provided that such handling is done quickly before U-232 daughters have a chance to build in. These U-232 daughters peak in concentration 10 years after irradiation. This module (K2) deals with the options for reprocessed uranium arising from aqueous reprocessing of LWR fuels. It will be seen that costs depend markedly on whether the U-232 daughters must be removed prior to further processing.

- Electrochemical molten salt-based processes are possible for the reprocessing of legacy LWR spent fuel; however, the lower decontamination factors for fission products and higher actinides mean that the reprocessed uranium would probably require remote handling during packaging and storage. Module K3 will deal with options for handling the reprocessed uranium arising from the electrochemical reprocessing of LWR and fast reactor oxide or metallic fuels.

- The price of natural uranium, U_3O_8 to UF_6 conversion, and uranium enrichment all affect the economics of reprocessed uranium use. If one or more of these prices are high, as is was the case 2 years ago (2004), the attractiveness of recycling (reconverting, reenriching, and refabricating reprocessed uranium into UOX fuel) versus reprocessed uranium storage or disposal is enhanced. Del Cul et al. describe such sensitivity studies (Del Cul 2007 and 2009).

- Recovery and reuse of REPU in the U.S. and Russia have been part of the military (nuclear weapons) fuel cycle for years. Recovery and reuse of legacy uranium materials are now also part of the U.S. Environmental Management (EM) program designed for remediation of the former U.S. Nuclear Weapons Complex. Some process and cost information from these programs will be discussed later in Section K2-6. Because military programs deal with uranium materials of higher enrichment (>20% U-235) there was very high economic incentive to recover and reuse the reprocessed highly enriched uranium (HEU), which was used originally as naval fuel or production reactor fuel.

An International Atomic Energy Agency (IAEA) technical document (TECDOC) report describes international efforts in the management of reprocessed uranium (IAEA 2007). Based on this document, the nations doing the most in this area are Russia, France, and Japan, which are the nations with the largest LWR fuel reprocessing capability

2012 AFC-CBD Basic Information. The 2009 AFC-CBR described in detail the technical and economic considerations associated with the storage, possible recycle, and possible permanent disposition of uranium arising from the aqueous reprocessing of LWR fuels. The choice between the options will be driven mainly by economic considerations, especially the price of natural uranium, for which RU is a substitute. A recent EPRI study [Machiels, 2010] describes these factors and other challenges associated with recycle of uranium and other actinides. The practice of uranium recycle has changed little from 2009. Russia is still the most active player in this area and still takes European RU for conversion, purification, re-enrichment, and refabrication of LWR fuel for use in European LWRs. [Department of Nuclear Power and Nuclear Fuel Cycle, 2010] is a proprietary Russian report (in English) describing the whole operation, its practical, environmental, and economic aspects, and the multiple process steps and facilities needed for its accomplishment. The author of this chapter highly recommends the purchase of this document from IBR to anyone who really wants to understand the details of uranium recycle. No US utilities or enrichers have publicly indicated interest in uranium recycle at this time, since the price of virgin (unirradiated) low-enriched uranium does not justify its consideration.

K2-2.   FUNCTIONAL AND OPERATIONAL DESCRIPTION

Reprocessed uranium in a nitrate solution is separated from fission products and other actinides in an early step in the separations part of the PUREX or UREX aqueous spent fuel reprocessing facility. This large stream can be stored in tanks as a liquid or evaporated to produce dry crystals of uranyl nitrate hexahydrate (UNH). The French LaHague plant already performs such a reprocessed uranium separation on a large scale (Nuclear France 2004 and Trowbridge and Del Cul 2003). The THORP facility, in the U.K. at Sellafield, also has this capability. There are several options for use or disposition of this reprocessed uranium nitrate material:

- **Temporary Storage**. The reprocessed uranium hexahydrate material can be converted to a more stable, solid chemical form and stored until a future decision on its ultimate fate (recycle or geologic disposal) is made. As with depleted uranium (Module K1), the chemical form of dry U_3O_8 powder has been determined to be the most stable and easy-to-handle form for storage. The French convert some of the LaHague reprocessed uranium in this manner and store the U_3O_8 in large (a few cubic meters) steel boxes at a Pierrelatte site warehouse where enrichment tails U_3O_8 are also stored. These reprocessed U_3O_8 boxes are surrounded by enrichment plant tails depleted U_3O_8 boxes, which are less radioactive storage boxes that act as shielding against the potent gamma radiation building up from U-232 decay daughters in the inner REPU-containing boxes.

- **Permanent Geologic Disposal.** The material can be packaged for permanent geological disposal. U_3O_8 is chemically stable; however, robust packaging or grouting of the powder would be needed to reduce fines, prevent leaching of radionuclides, and reduce radon emanation. Near-surface burial of low-level waste-type packages as Class A radioactive waste, such as is proposed for enrichment tails depleted U_3O_8 (Module K1), might not be permissible. The reader should note that even the disposal of enrichment plant derived DU or its compounds as Class A LLW is still an environmental and regulatory issue, as discussed in Module K-1. For current LWR fuel burnups, small amounts of plutonium, neptunium, and technetium, in addition to the usual uranium decay products of radon make this reprocessing-derived material considerably more radioactive than enrichment plant depleted U_3O_8, which should have no or extremely small amounts of fission products or transuranics present. It is likely that low-level waste disposal sites, such as Envirocare and Barnwell, could not

presently accept this type of waste under current regulations.[a] A deep or tunneled geologic repository-type environment like Yucca Mountain would be more appropriate, and the heat load associated with this material would be orders of magnitude smaller than for high-level waste or spent fuel. U-234 is the radioisotope that would present the longest range radiotoxicity hazard. U-232 daughters remain a problem for only 300 years. No nation is currently pursuing this permanent reprocessed U permanent disposal option. If such a geologic disposal option is pursued, retrievability of the material would be an advantage, since in the future the fertile uranium content might be needed for breeder reactors. LWR-reprocessing derived DU is just as valuable as enrichment plant tails-derived DU for a future breeder fuel resource, and the former adds about 10% more material to the latter in overall resource sustainability terms. Geologic disposal of REPU was re-examined from a cost standpoint in 2015 (Schneider and Williams 2015)

- **Preparation for Recycle as LWR UOX Fuel.** The reprocessing-derived UNH can be converted to a form, such as UO_3, suitable for fluorination/purification (similar to Module B) to reprocessed UF_6 and reenrichment to a U-235 level somewhat above the LEU level required for "virgin" UOX fuel derived from natural uranium (similar to Module C). The extra enrichment is needed to compensate for the neutron absorption by U-236. The reprocessing-derived and re-enriched UF_6 can be refabricated into LWR UOX fuel in a conventional fuel fabrication plant if the small amount of U-232 remaining after purification is isotopically separated in the enrichment process or clean EUF_6 blendstock from elsewhere in the fuel cycle is added. These re-enrichment options are discussed in detail in Module D1-1 (LWR UO_2 Pellet Fuel Fabrication) and in a report by de la Garza (1977). The French (AREVA) sent some of their reprocessed U_3O_8 to Russia (Seversk) for conversion and purification (removal of U-232 daughters), followed by enrichment in a "double cascade" of gas centrifuges, which produce an enriched U-235 product with very low U-232 content. The Russian company, TVEL, fabricates this enriched UF_6 into fuel assemblies, which are burned in reactors in Sweden, Switzerland, Germany, and France (IBR 2006 and 2008). As the prices of enrichment and uranium ore rise, this option becomes increasingly attractive. Only one recycle of reprocessed UOX fuel is presently preferred because of the accumulation of the U-236 "poison" isotope that would occur with multiple recyclings. Note that the U.S. gaseous diffusion enrichment plants in the past have also re-enriched REPU from European customers, as well as re-enriching military REPU from production reactors (Williams 1999 and Diehl 2005).

- **Diluent UO_2 for MOX Fuel.** The reprocessed uranium can be used as the "diluent" for $(Pu, U)O_2$ or $(Pu, Np, U)O_2$ mixed oxide (MOX) fuel for either thermal or fast reactors. This utilization scheme can be accomplished by conversion of the nitrates to oxide and physical blending or by coprecipitation directly from the reprocessing plant nitrate solutions. For Co-Ex reprocessing, this would be the preferred option—only a fraction of the REPU product from LWR fuel reprocessing would be required. The cost for this step was reexamined in 2012.

The Consolidated Fuel Treatment Center (CFTC) Engineering Alternative Studies (EAS) utilized a thermal de-nitration process to convert the uranium nitrate solutions from reprocessing to UO_3 powder. The U oxide was packaged in drums containing 400 kg U each. The product could be re-enriched for UOX fuel, used in a MOX fuel or disposed as described above.

K2-3.   PICTURES AND DIAGRAMS

Figure K2-1 shows schematically the possible disposition paths for LWR spent fuel reprocessing-derived reprocessed uranium. The paths were described in the subsection above.

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a. Envirocare at Clive, UT has been allowed to accept reprocessing-derived depleted UO_3 from the Savannah River Site (SRS). Since the depleted-U target burnups in the SRS production reactors were extremely low (short irradiation times for Pu-239 production), the amounts of TRU and fission products in this material are low. (Knoxville News-Sentinel 2009)
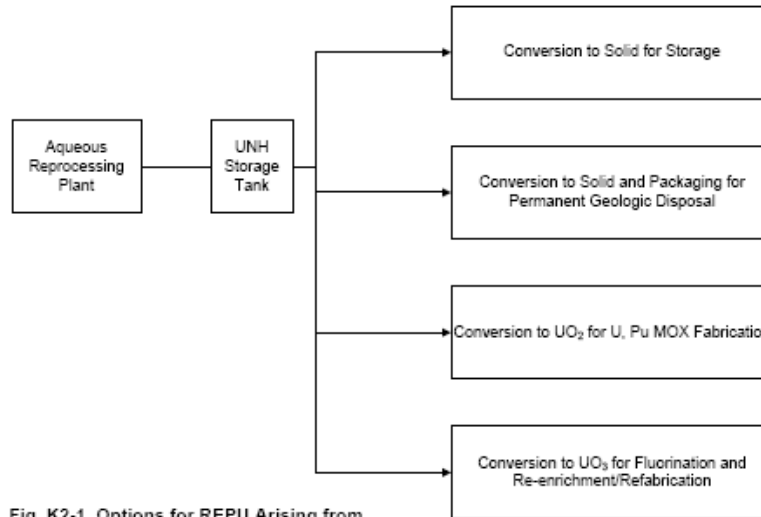
Fig. K2-1. Options for REPU Arising from
Aqueous Reprocessing of LWR Fuels

Figure K2-1. Options for reprocessed uranium arising from aqueous reprocessing of light-water reactor fuels.

K2-4.   MODULE INTERFACES

Front-end interface. The aqueous spent fuel reprocessing plant (Module F1) represents the front-end interface. The cost analyst should ensure the reprocessed uranium conversions (from stored uranyl nitrate hexahydrate to UO_3, U_3O_8, UF_6, or other form) are not already included in the \$/kgHM cost of the reprocessing steps, since these conversion steps could conceivably be undertaken at the reprocessing complex (as is done in some foreign plants). Transportation of an evaporated solid to an off-reprocessing plant site location for further treatment or storage would likely be in the form of UNH crystals by commercial carrier in lined and sealed drums. This transportation/packaging cost (see Module O) should be assigned to this module and is expected to be very small if these steps are taken soon after reprocessing and the U-232 daughters have not yet had a chance to form in radiologically significant amounts.

Back-end interface. Preparation, storage, or disposal of the reprocessed U_3O_8 powder resulting from conversion of uranyl nitrate hexahydrate, all have their own technical, regulatory, and procurement issues. U_3O_8 would most likely be prepared by ammonium nitrate precipitation of a double uranium salt (ADU) followed by calcination and adjustment of oxygen stoichiometry. UO_3, for later fluorination to UF_6, or UO_2 for preparation of MOX, could both be prepared in the same manner with careful adjustment of oxygen stoichiometry. If the uranyl nitrate hexahydrate feed material has been sitting around long enough for U-232 daughters to build in, it would be advisable to aqueously "polish" a uranyl nitrate hexahydrate solution by using solvent extraction or ion exchange to remove the U-232 daughters. In this manner subsequent processing operations could involve less radiation dose to workers.

As with depleted U_3O_8 derived from enrichment plant tails, the environmental feasibility and regulation of the shallow geologic disposal of large amounts of bulk U_3O_8 or other uranium forms remains highly problematic (i.e., discussion in Module K-1). The U-232 daughters and higher U-234 and U-236 content of this material make the problem much more serious than for enrichment plant "virgin" tails derived DU_3O_8. This material may have to be handled as greater-than-class-C (GTCC) low-level waste; however, no such regulations have been developed for it. As with the tail materials (>100,000 of MTU), the very large inventory of this reprocessed material (>10,000 of MTU) and its possible potential concentration into one geographic area means that in the distant future (thousands of years), after the containers enclosing the insoluble depleted U_3O_8 corrode away, the burial area will be a large producer of radon gas from the uranium decay chain. This gas would easily diffuse through any dry soil cap. In order

to prevent this occurrence, a deeper or less-permeable capped burial site or noncorrodible containers will be needed. U-234 would also present a long-term radiotoxicity hazard similar to that from higher actinides, such as neptunium, in a spent fuel repository. For this reason, long-term sequestration of reprocessed U_3O_8 in a deep mine or tunnel-type repository is likely to be required. The lack of high-heat generating radioisotopes; however, means that such material could be efficiently emplaced in a geologic repository without major spacing issues.

An option not yet considered might be to blend enrichment tails-derived U_3O_8 (Module K-1) with reprocessed U_3O_8 for shallow burial. The former much less radioactive material is likely to be available in amounts ten or more times that of the latter. A "blend" might meet the allowable radionuclide limits for the less-expensive shallow burial option.

The reprocessed uranium disposal options above should not be confused or double-counted with those in Modules G3 (LLW Conditioning, Storage, and Packaging), J (Near Surface Disposal), or L (Geologic Repository). The costs for Module K2 disposal options take the material all the way to final disposal and Modules G3, J, or L costs should not be superimposed.

If recycle is warranted, the costs for this Module K2 step include conversion of the UNH to an oxide and fluorination of this oxide all the way to reprocessed UF_6. If the UNH feed has accumulated U-232 decay daughters, the fluorination process can be designed to remove them, thus reducing the radioactivity level in the enrichment and fuel fabrication facilities. Costs for re-enrichment and fuel refabrication are covered in Modules C1 (Uranium Enrichment) and D1-1 (LWR UO_2 Pellet Fuel Fabrication). The use of REPU as a substitute for natural (virgin) feed is discussed briefly in Module A (Uranium Mining and Milling). Use of reprocessed uranium is anticipated to raise these unit separative work ($/SWU) and unit fabrication costs ($/kgHM) by up to 20% above that for virgin feed-derived materials.

K2-5.   SCALING CONSIDERATIONS

No data are available. Any reprocessed uranium conversion facilities are likely to be located on the reprocessing plant site; hence, sizing might be similar to that for Module F1.

K2-6.   COST BASES, ASSUMPTIONS, AND DATA SOURCES

The unit cost figure of merit of interest (and its value) for this step depends on which of the above options is chosen and the extent to which the material is contaminated with undesirable radionuclides. Each option will be separately discussed below.

Temporary Storage. Temporary storage costs will depend on how long the material is stored. An owner of separated reprocessed U_3O_8, the most likely reprocessed uranium storage form, will save it until the price of natural U_3O_8 rises to the point that recycling of reprocessed uranium as UOX fuel is economically beneficial. An Oak Ridge National Laboratory report (Spencer et al. 2005) describes some engineered product storage forms and options for this material, but does not include cost estimates. An earlier Oak Ridge National Laboratory report (Michaels and Welch 1993) suggests that less-radioactive, contact-handled material, which can be stored in containers with a surface radioactivity of 200 mrem/hr or less, can be bulk-stored in vaults at a capital cost of $3/kgU in today's (2008) dollars.

The CFTC studies (WSRC 2008) indicated that bulk warehouse storage TPC would be in the range of $5.6M to $6.4M for a 5 year capacity (3,700MT). This equates to a capital cost of $1.50 to $1.75/kg U.

In light of other uranium storage capital costs, such as for less-radioactive depleted uranium products, these costs are determined to be low. A value of $6/kgU is appropriate given today's more stringent regulations and building standards (which are still evolving). The ORNL report also suggests that at a storage fill rate of ~2,000 MTU/yr, the facility would incur operational costs of $5M/yr (2008 dollars) during filling and $1.5M/yr (2008 dollars) during surveillance only. The CFTC studies confirm these O&M costs with a range of $5.1M to $6.4M/yr for a storage facility in active operations (studies assumed a single warehouse with constant receipts/shipments since disposition paths were assumed to be

available.) These operation costs seem to be reasonable for what is only a logistical/surveillance task. Assuming a 40-year storage time for each kgU before a decision to recycle or dispose, the total storage capacity would need to be 80,000 MTU. The storage facility would operate for 120 years, with 40 years to fill, 40 years of surveillance only, and 40 years to empty. This gives an average operations cost of $6/kgU for each kgU emplaced. The total (capital + operations) unit cost then calculates as $12/kgU, assuming a 40-year storage time. This cost seems reasonable compared to the $5–9/kgU range for handling less-radioactive enrichment plant tails-derived depleted U_3O_8. The reprocessed U_3O_8 unit cost, however, does not include any ultimate disposal costs. As will be seen below, these final disposition unit costs can be more substantial.

A calculated annual unit cost value of $16/kgU/yr was reported by the Generation IV Fuel Cycle Crosscut Group for "separated uranium" (DOE 2002). For 40 years this would represent a cost of $640/kgU. This is more than many national cost estimates (in terms of kgHM) for disposing of spent fuel. Either the "per year" term was mistakenly added, or the value is inordinately high and would be for highly contaminated uranium (i.e., uranium with substantial remaining fission products, very high U-232 content, and/or higher actinides). Note that this module (K-2) is discussing well-known chemical technology for which the radioactivity hazard (and handling costs) can be minimized by "early" treatment (aqueous removal of U-232 daughters) and for which nuclear criticality concerns are non-existent for feedstocks of U-235 content 0.9% or less.

Permanent Geologic Disposal. Michaels and Welch suggests that reprocessed U_3O_8 could be disposed in a deep or tunnel type geologic repository for $72/kgU in 2008 dollars ($53/kgU in 1993 dollars) (Michaels and Welch 1993). This would presumably include the waste package and transportation from the storage location. No mention was made of whether this material could be collocated with spent fuel in a Yucca Mountain type geologic repository. By the time a decision is made whether to store or recycle (tens of years) the U-232 daughters will have built up to the point that a remote handling facility might be needed to empty the U_3O_8 storage containers or vaults, which might be volumetrically large, into volumetrically smaller, more robust packages for repository emplacement.

For comparison, costs of $15/kgU (2007 dollars) ($11/kgU [1993 dollars]) were given for geologic disposal of the less-radioactive depleted U3O8 derived from uranium enrichment operations. (Expensive deep or tunnel disposition of enrichment-derived [tails] depleted U3O8 will hopefully never be necessary. See Module K-1 for discussion of this material and its disposition paths and costs.) Unit costs for disposing the DUO3 reprocessed material from SRS should also be in the low range of possible costs for REPU disposal.

Preparation for Recycle as Light Water Reactor UOX. The cost of the conversion/processing service required before enrichment will depend on how long the material has been stored since reprocessing. Again, the handling difficulty, and hence cost, is driven by the concentration of the U-232 daughters in the uranyl nitrate hexahydrate at the reprocessing plant or the U3O8 at the storage site. According to Michaels and Welch, a "new" recently-separated uranium electrochemical processing product (U-metal) can be converted to U3O8 for $8/kgU (2008 dollars) (Michaels and Welch 1993). This would also represent a reasonable unit cost for converting "new" uranyl nitrate hexahydrate to UF6. If stored "old" U3O8 or UNH needs to be converted to UF6, aqueous polishing will be needed to remove the U-232 daughters. This could drive the unit cost up to $41/kgU (2007 dollars). To calculate the total UOX fuel cost, enrichment, and refabrication costs would need to be added (Modules C1 and D1-1). This option is further discussed in Trowbridge and Del Cul's reports (Del Cul 2007) and Module D1-1 (Trowbridge and Del Cul 2003).

The CFTC studies (WSRC 2008) indicated a thermal de-nitration process for conversion of recently reprocessed U nitrate solutions into UO3 powder and packaged into drums containing 400kg each has a total capital cost between $250M to $330M and an annual O&M cost of between $29M and $43M/yr for a reprocessing plant capacity of 800MT/yr. The total LCC (TPC+ O&M + D&D) ranged from $1.7B to

$2.5B for 40 years of operations. This equates to a capital cost component of $8.5 to $11.20/kg U or a total LCC unit cost of $12.4 to $16.9/kg U.

Reprocessed UO2 would make an excellent fuel for CANDU reactors. No additional enrichment would be needed, since the U-235 content of reprocessed uranium fits the requirements of CANDU designs. (This cost is analyzed in Del Cul et al.'s report [2007].) Since there would be no need to enrich LWR REPU for use in CANDUs, the economics of this application are even more attractive than those for REPU recycle in LWRs. In addition, there is no need to deal with enrichment plant tails. The major savings is the avoided cost of purchasing uranium ore. Pursuit of this option by Canada would allow more Canadian ore to be sold on the international market, since domestic use could be cut significantly. Table K2-1 shows that for high ore prices ($233/kgU assumed) the unit cost associated with REPU use is half that for CANDU fuel assemblies derived from virgin (mined) U3O8 (Module D1-7). This is true even if fabrication of REPU incurs a higher unit cost because of the radiation hazard associated with U-232 daughters.

Table K2-1 Comparison of CANDU unit fuel costs from reprocessed and virgin uranium (circa 2008).

Economics of the Use of LWR Reprocessed U in CANDU Reactors		
NATURAL U CANDU FUEL FROM URANIUM ORE:		
Uranium ore price (English)	89.6	*$/lb U3O8*
Uranium mine & mill price (Metric) (as if U3O8 produced)	233	$/kgU
Canadian conv of U-mill solutions to pure reactor-grade UO2	10	$/kgU
CANDU fuel fabrication price (from UO2 powder)	100	$/kgU
Total cost	**343**	$/kgU
CANDU FUEL FROM LWR REPROCESSED U*		
Dissolution of REPU3O8, cleanup of sol'n, and conversion to UO2 of right powder morphology	40	$/kgU
CANDU fuel fab price (adj for higher handling risk)	130	$/kgU
Total cost	**170**	$/kU
* No enrichment step assumed. ~0.7%-0.9% U-235 in REPU; some U-236 present		

Use as a Diluent for Contact-Handled MOX Fuel. As for UOX recycle above, the unit cost to make a material suitable to refabrication into contact-handled fuel would depend on how long it has been since the uranium product was separated during reprocessing. If the time is very short, a fuel grade, "moxable" UO_2 powder could be prepared from uranyl nitrate hexahydrate for around $40/kgU. (Note that this conversion cost is higher than the $7 to $17/kgU [mentioned above] just required to alter the chemical form. It also includes the costs to produce a flowable, sinterable [i.e., "moxable"], UO_2 powder that meets the ASTM fuel specification, thus the > $23/kgU premium.) If old, U-232 daughter-laden feed material is used, another $35/kgU would be required for aqueous polishing prior to powder preparation. If these numbers are used in an analysis, care should be taken to remove the part of the unit MOX fabrication cost (Module D1-2) that comprises the depleted U_3O_8 to "moxable" depleted UO_2 powder step. Around $30 to $70/kgHM of the overall MOX fab cost is attributable to this operation if the MOX plant receives enrichment plant tails derived depleted UF_6 or depleted U_3O_8 as the PuO_2 diluent.

Limitations of Cost Data and Other Considerations. The following considerations are relevant to reprocessed-uranium materials in the fuel cycle:

1. Because of U-236 buildup, it is likely that reprocessed UOX could undergo, at most, two recycles. If a highly selective method for uranium enrichment, such as a laser-based process, became available (one that could selectively remove U-236) more recycles of UOX would become feasible.

2. The reprocessing technology must keep levels of fission products and higher actinides low enough (in the uranium product) to allow contact-handling and favorable economics.

In general, the reprocessed uranium disposition step of the fuel cycle can be placed in the viable-commercial category of technology readiness. Uranium ore and enrichment prices will help dictate when and how reprocessed uranium is dispositioned. The UK Nuclear Decommissioning Authority (NDA) is presently performing such trade-off studies to inform their decision how to deal with the 35,000 MT of REPU arising from reprocessing of Magnox and Advanced Gas Reactor fuel (IDM 2007).

REPU utilization/disposition experience in the U.S.: Some useful insights can be gained from the disposition of military REPU streams in the U.S. Nuclear Weapons Complex. As mentioned earlier, this government-based REPU utilization/disposition activity is the only one taking place in the U.S. Two programs are underway to utilize and disposition the reprocessed uranium from the Savannah River Site (SRS), which formerly produced weapons-grade plutonium and tritium in production reactors. These reactors had both driver fuel, which provided the neutrons to transmute U-238 to Pu-239 and Li-6 to tritium (H-3) and target fuel, which consisted of mostly depleted-U to be transformed to plutonium by those neutrons. The driver fuel consisted of highly enriched U, which after several cycles still had enough recoverable U-235 present to make reprocessing economically viable. The uranium solution resulting from reprocessing was well over 20% U-235, and could be re-enriched, reconverted, and refabricated into new production reactor fuel. When the production reactors were shutdown in the late 1980s, the HEU solution was saved in tanks for later processing. After the DU targets were processed, and the plutonium and fission products separated out, the remaining depleted uranium nitrate (DUNH) solution was calcined to UO_3, drummed, and warehoused. Figure K2-2 below shows the steps and facilities involved in this process.
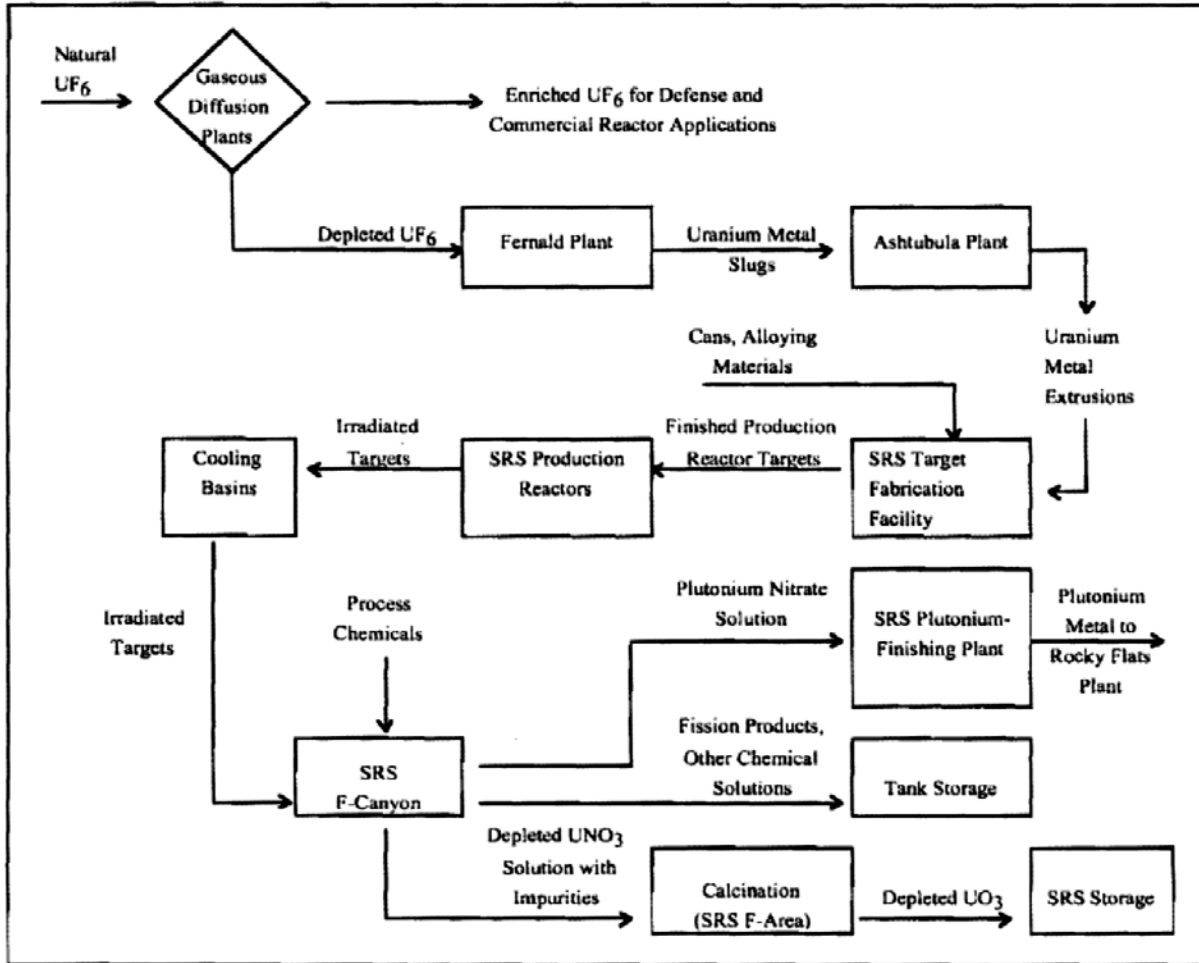
Figure K2-2 Former DU-related steps at Savannah River Site and other Weapons Complex Sites (White 2009).

The HEU solution, after some cleanup at SRS, is now being blended with natural U to prepare LWR enrichment-grade fuel for commercial reactors. A Nuclear Regulatory Commission (NRC)-licensed facility at Erwin, Tennessee (Nuclear Fuel Services) is performing the blend-down with a sister AREVA facility producing fuel for reactors owned and operated by the Tennessee Valley Authority (TVA). After conducting a lead test assembly program, TVA was given permission to burn this "off-spec" uranium as part of Project BLEU (Blended Low-Enriched Uranium). All of this is being done under the auspices of the Department of Energy (DOE) National Nuclear Security Administration (NNSA) Fissile Materials Disposition Program. From an economics standpoint, TVA benefits from very cheap fuel, and DOE-NNSA benefits from disposing of large amounts of legacy materials that were sitting in tanks. It should be noted that reprocessed HEU from Naval Nuclear Programs can also be treated in the same manner.

The drummed reprocessed DUO_3 is also destined to leave the SRS (SRS 2002). According to recent announcements, the material is to be shipped via rail to the Energy Solutions Clive, Utah, LLW "Envirocare" disposal site. Because of the short irradiation time in the production reactors, the amount of U-236, U-232, and fission product left in this material after processing is so small that it can be handled as LLW. However, there is some public concern because of the long-term radon issue. In 2010 over 8000 MTU of this material will be shipped from SRS warehouses to Envirocare for burial (Fahys; Salt Lake Tribune 2009). From recent contract announcements (U.S. DOE 2009), it appears that the transportation cost for this material must be on the order of 40 cents per kg U.

K2-7.   DATA LIMITATIONS

No information provided.

K2-8.   COST SUMMARIES

Some new cost data has been gleaned from various literature sources since 2009. Nearly all of it is associated with the cost of solvent extraction purification (U-232 daughter removal by aqueous polishing) and the conversion of the resultant clean product to UF6 for introduction to an enrichment facility. Unit cost data from WISE (Europe), EPRI (USA), and IBR (Russia) are presented in the Table K2-2. The IBR data had to be adjusted to fit the scope of work described in the left side of the table.

Table K2-2. Aqueously-reprocessed uranium unit handling costs per references (from 2012 AFC-CBD) Update).

Study or Ref /Year	Low Value ($/kgU)	Reference Value $/kgU $/kgU	High Value ($/kgU)
Aqueous polishing and conversion of UNH product from aqueous reprocessing plant to UF6 for re-enrichment (WISE fuel cycle calculator default value)	N/A	39	N/A
Same process as above (EPRI Report 1020659)	15 (would be 5 for NATU w/o aqueous polish)	45	60 (would be 20 for NATU w/o aqueous polish)
Same process as above: (IBR/Moscow Report IBR 2006 & 2008)	38	45	60
Clean UNH to MOX quality UO2 powder (communication from NNSA NA-26 Pu-disposition program)		60	

The last row of the table includes data for converting reprocessed UNH to a UO2 powder form for the production of MOX. This can be accomplished by either a "wet" (aqueous) or "dry" chemical process. The stringent powder morphology and impurity standards for MOX fuel UO2 account for the high unit cost. The $60/kgU value is an approximate figure given to the author by a participant in the NNSA MOX Program for disposition of US weapons plutonium. (The US program uses depleted UO2 as the MOX diluent rather than UO2 from RU; however, the processes and resultant costs would be similar.)

Table K2-3. Cost summary table for reprocessed uranium disposition options (Constant 2008 dollars).

Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
Conversion of UNH to U_3O_8 storable form: "New" UNH to U_3O_8 "Old" UNH to U_3O_8 including removal of U-232 daughters		$4/kgU $20/kgU	$17/kgU $50/kgU	$12/kgU $40/kgU
Reprocessed U_3O_8 40-year Storage $6/kg U for 80,000 MTU/yr Storage Capacity. Annual costs of $1.5M to $5M/yr	In unit cost, amount unknown, but not felt to cover all risks	$7/kgU if shallow burial allowed	$30/kgU if facility regulation and construction difficulties ensue or very long-term storage is required	$9/kgU
Aqueously–derived reprocessed U_3O_8 Permanent Geologic Repository Disposal	In unit cost, amount is unknown	$61/kgU if above temporary storage package could be emplaced	$72/kgU if regulatory and siting difficulties arise	$93/kgU including repackaging, transportation, emplacement, and perpetual surveillance
Preparation for UOX recycle: "New" product to UF_6 (no aq polish) "Old" product to UF_6 (aq removal of U-232 daughters)	In unit cost, amount is unknown	$6/kgU $30/kgU	$20/kgU $60/kgU	$14/kgU $50/kgU
UOX diluent for MOX fuel: "New" product for immediate contact-handling to "moxable UO_2" "Old" product processing requiring removal of U-232 daughters prior to contact-handling	In unit cost, amount is unknown	Not available	Not available	$40/kgU $75/kgU

The What-it-takes Table K2-4 for the 2012 AFC-CBR is changed very little from the corresponding Table in the 2009 AFC-CBR (Table K2-3). Since no new cost data sources were found for RU storage or disposal it was decided to keep the 2009 values. Since escalation from the 2008 to 2012 time frame has been minimal, the 2009 AFC-CBR unit costs are not adjusted. Only three table entries have been changed to reflect new cost information. The $45/kgU "nominal" value for purification and conversion to UF6 is supported by multiple data sources in Table K2-2. The MOX-UO2 related conversion unit costs for RU has been changed as a result of recent data from the NNSA MOX program. Costs have been lowered to reflect K1-2 DU oxide disposal costs plus a premium to handle the higher specific activity of reprocessed material.

Table K2-4. Cost summary 'What-It-Takes' (WIT) table for aq. reprocessed uranium disposition options (Constant 2012 dollars).

U-Handling Step	Upsides (Low Cost)	Selected Value (Nominal Cost)	Downsides (High Cost)
Conversion of UNH to U308 storable form:			
"New" UNH to U308	$4/kgU	$12/kgU	$17/kgU
"Old" UNH to U308 including removal ofU-232 daughters	$20/kgU	$40/kgU	$50/kgU
Reprocessed U$_3$0$_8$ 40-year Storage: Based on $6/kg U for 80,000 MTU/yr Storage Capacity. Annual costs of $1.5M to $5M/yr	$7/kgU if temporary shallow burial allowed	$9/kgU	$30/kgU if facility regulatory and construction difficulties ensue or very long term storage is required
Aqueously-derived reprocessed U308: Permanent Geologic Repository Disposal	$61/kgU if above temporary storage package could be permanently emplaced	$72/kgU including repackaging, transport, emplacement, and perpetual surveillance	$93/kgU if regulatory and siting difficulties arise with "nominal" option
Preparation for RUOX recycle (pre-enrichment):			
"New" product to UF$_6$ (no aq polish)	$6/kgU	$14/kgU	$20/kgU
"Old" product to UF6 (aq removal ofU-232 daughters)	$30.kgU	$45/kgU (new for 2012)	$60/kgU
Conv to High grade UO2 powder diluent for MOX fuel:			
"New" product for immediate contact-handling to "moxable UO2":	N/A	$60/kgU (new for 2012)	N/A
"Old" product processing requiring removal ofU-232 daughters prior to contact handling	N/A	$95/kgU (new for 2012)	N/A

Table K2-5 shows the above costs escalated to 2017 from 2009$ for most entries using the factor of 1.14 from the "Escalation Considerations" data in the Main Report. The REPU disposal values have been adjusted to take into account the new knowledge gained from the research to prepare Module K1-2 (Depleted Uranium Oxide Geologic Disposal).
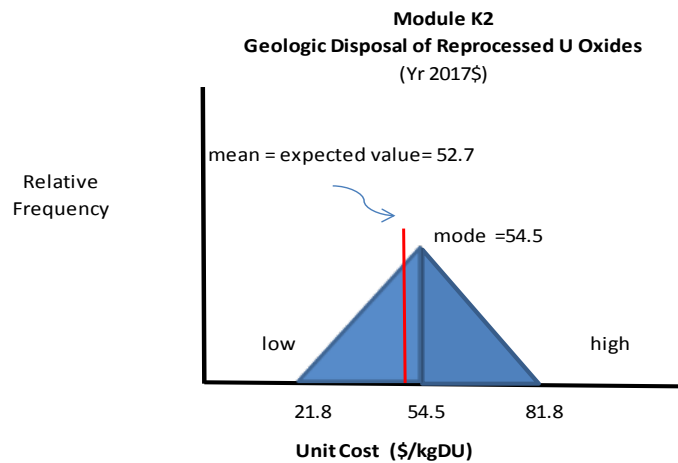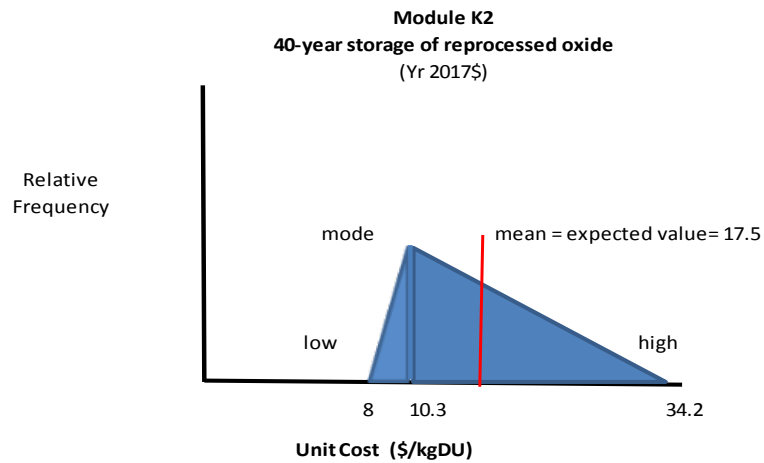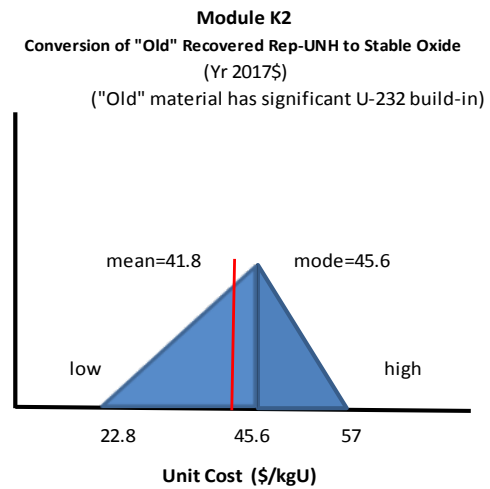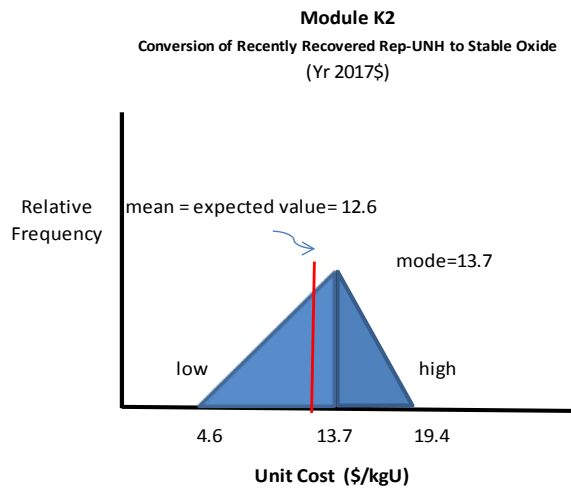
Table K2-5. Cost summary What-It-Takes (WIT) table for aq. reprocessed uranium disposition options (Constant 2017 dollars).

U-Handling Step	Low Cost	Mode Cost	Mean Cost	High Cost
Conversion of UNH to U308 storable form:				
"New" UNH to U308|	$4.6/kgU	$13.7/kgU	$12.6/kgU	$19.4/kgU
"Old" UNH to U308 including removal ofU-232 daughters	$22.8/kgU	$45.6/kgU	$45.6/kgU	$57.0/kgU
Reprocessed U_3O_8 40-year Storage: Based on $6/kg U for 80,000 MTU/yr Storage Capacity. Annual costs of $1.5M to $5M/yr	$8.0/kgU if temporary shallow burial allowed	$10.3/kgU	$17.5/kgU	$34.2/kgU if facility regulatory and construction difficulties ensue or very long term storage is required
Aqueously-derived reprocessed U308: Permanent Geologic Disposal (Reassessed using new data from 2015) (DUF6 deconversion/disposal study)	$21.8/kgU if above temporary storage package could be permanently emplaced. In shallow trench or borehole	$54.5/kgU including repackaging, transport, emplacement, and perpetual surveillance in mined repository	$52.7/kgU	$81.8/kgU if regulatory and siting difficulties arise with "mode" option
Preparation for RUOX recycle (pre-enrichment):				
"New" product to UF_6 (no aq polish)	$6.8/kgU	$16/kgU	$15.2/kgU	$22.8/kgU
"Old" product to UF6 (aq removal ofU-232 daughters)	$32.7.kgU	$49/kgU (new for 2012)	$49/kgU	$65.4/kgU
Convert to High grade UO2 powder diluent for MOX fuel:				
"New" product for immediate contact-handling to "moxable UO2":	N/A	$65.4/kgU		N/A
"Old" product processing requiring removal ofU-232 daughters prior to contact handling	N/A	$103.6/kgU		N/A

K2-9.   SENSITIVITY AND UNCERTAINTY ANALYSES

Uncertainty Results from 2009 AFC-CBD: CFTC studies developed a cost estimate range using contingency as the primary difference between the low and high range. Based upon past nuclear project experiences for nth of a kind, low radiation facilities a contingency of 5% for the TPC low range and 30% for the TPC high range was established. An uncertainty range for the LCC estimate components was established as ±20% of the nominal estimate. These are shown in Table K2.3 in year 2008 dollars.

Uncertainty Results from 2012 Update to AFC-CBD: For uncertainty analyses triangular distributions should be used. Escalation from 2008 to 2012 was virtually zero. The triangular distributions in Figure K2-3 have been updated with this 2017 edition.

Module K2

Conversion of Recently Recovered Rep-UNH to Stable Oxide

(Yr 2017$)

Relative Frequency

mean = expected value= 12.6

mode=13.7

low   high

4.6   13.7   19.4

Unit Cost ($/kgU)

Module K2

Conversion of "Old" Recovered Rep-UNH to Stable Oxide

(Yr 2017$)

("Old" material has significant U-232 build-in)

Relative Frequency

mean=41.8   mode=45.6

low   high

22.8   45.6   57

Unit Cost ($/kgU)

Module K2

40-year storage of reprocessed oxide

(Yr 2017$)

Relative Frequency

mode   mean = expected value= 17.5

low   high

8   10.3   34.2

Unit Cost ($/kgDU)

Module K2

Geologic Disposal of Reprocessed U Oxides

(Yr 2017$)

Relative Frequency

mean = expected value= 52.7

mode =54.5

low   high

21.8   54.5   81.8

Unit Cost ($/kgDU)

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Module K3

Electrochemically Reprocessed Uranium Conversion, Disposition, and Possible Recycle

Module K-3
Electrochemically Reprocessed Uranium Conversion, Disposition, and Possible Recycle

K3.MD SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest (2009 AFC-CBR) technical update from which this 2017 update was escalated:**
  - Conversion and **storage costs** were based on literature survey and some adjustments made in 2009 AFC-CBR. Moxable UO2 preparation costs were revisited in 2012 AFC-CBR.
  - Geologic disposal costs were based on E. Schneider and K. Williams' 2015 analysis cited in the K1 module. **A view graph report of this analysis is a supplementary document to this 2017 AFC-CBR. (2017-CBR-SD-7)**
-

K3.RH REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared:** 2006 as Module K3.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2009
- **New technical/cost data which has recently become available and will benefit next revision: at this point no new data.**

K3-1. BASIC INFORMATION

2009 AFC-CBD Introduction. For light-water reactor (LWR) fuel cycles and many fast reactor fuel cycles, uranium is the largest resulting constituent of the irradiated spent fuel heavy metal mass. If it is separated during reprocessing of spent fuel, it is known as "reprocessed uranium" or "REPU." For LWRs operating on enriched uranium oxide (UOX), only a small fraction of the total initial uranium radioisotopes are fissioned or transmuted to other actinides. After discharge from the reactor, typically over 93% of the heavy metal mass (not including zircalloy cladding or fuel assembly structures) is uranium. In the spent fuel pools of U.S. LWRs, there is already over 40,000 MTU (in 2006) of this material that might be ultimately recovered as reprocessed uranium during reprocessing.

For fast reactor cycles operating on uranium, plutonium mixed oxide fuel in the "breeder" mode, the uranium fraction in the driver fuel is typically 50 to 85% of the initial preirradiation heavy metal mass. For lower conversion ratio fast reactors utilizing higher actinide (Pu, Np, Am, Cm) fuels, the uranium content is likely to be smaller than for a "breeder." The blanket fuel starts out as 100% uranium (most likely depleted uranium) and higher actinides, such as Pu-239, are produced by neutron absorption during irradiation. Both fast reactor driver fuel and blanket fuel need to be reprocessed: (1) to get the useful fissile plutonium from the blankets, and (2) to remove fission products and some of the less-desirable, U-232 and U-236 laden uranium from both the drivers and blankets. The remaining fissile mass can be refabricated into new drivers. The "discard" uranium mass can be made up by fabricating new depleted uranium blankets and by adding clean uranium to the refabricated driver fuel. In the U.S., there is very little fast reactor spent fuel, and what there is has limited irradiation exposure. The Experimental Breeder Reactor-II fast reactor was probably the most successful demonstration of U.S. fast reactor technology.

The Fast Flux Test Facility (FFTF) also operated well, but was shut down early because of lack of funding. For fast reactors that are to be operated as "burners" rather than "breeders," the actinide fissile content of the fuel is likely to be higher and the initial uranium content lower. This higher fissile content ensures that there are enough neutrons available to destroy (fission or transmute) the undesirable higher actinides and transmute certain long-lived fission products.

For metal-fueled fast reactors, there is likely to be uranium separated out in the aqueous or electrochemical reprocessing step (Module F2/D2). The choice of an electrochemical process depends on whether metal or ceramic fuel is being considered and what other alloying constituents, such as zirconium, are in the fuel mass. Regardless of the reprocessing method, the following factors affect the nature of the reprocessed uranium that can be obtained from reprocessing:

- The initial U-235 assay of the fuel before irradiation (this is one of the variables which will determine the post-irradiation U-235 assay and the concentrations of other uranium isotopes).

- The burnup level of the spent fuel (this also determines the fractions of the various isotopes of uranium in the irradiated uranium). The higher the burnup, the smaller the ratio of the postirradiation U-235 content to the preirradiation U-235 content.

- The initial U-235 assay and the burnup also determine the amounts of the undesirable isotopes U-232 and U-236 that are formed. Short-lived U-232 has radiologically potent decay daughters. such as thallium-208. which complicate reprocessed uranium handling. U-236 is a neutron poison (absorber) that adversely affects the performance of any new UOX or mixed oxide or metal fuel that is produced from reprocessed uranium. The higher the initial U-235 assay and burnup, the more of these undesirable, nonnatural isotopes are produced.

- The nature and chemistry of the reprocessing scheme (the associated "decontamination factors" determine the amounts of nonuranium impurities, such as fission products and higher actinides, such as plutonium and neptunium carried over into the reprocessed uranium stream). Aqueous processes such as UREX and plutonium-uranium extraction (PUREX) have higher decontamination factors for separating uranium from fission products and higher actinides. The very low quantities of nonuranium impurities mean that any further handling of the reprocessed uranium stream can be in "contact-handling" facilities, provided that such handling is done quickly before U-232 daughters have a chance to build in. These daughters peak in concentration approximately 10 years after irradiation.

Electrochemical processes (Module F2/D2) have been proposed for the reprocessing of legacy LWR spent fuel and the reprocessing of fast reactor blanket (or higher actinide targets) and driver fuel. These dry processes involve molten salt chemistry and electrochemistry and can be used to reprocess oxide or metal fuels. However, they seem to be better suited for the latter type metal fast reactor fuels. Electrochemical processes experience lower decontamination factors for fission products and higher actinides (from uranium). This means that electrochemically-derived reprocessed uranium would contain more residual radionuclides and probably require remote handling during packaging and storage. These lower decontamination factors are not a problem for many fast reactor cycles, because the fuel must be handled remotely from irradiation through refabrication anyhow, and the presence of small fractions of fission products or higher actinides does not pose a safety or personnel exposure problem. Also, some of the uranium can be directly recycled and does not even have to be totally separate from other actinides during the recycle/refab operations. This Module K3 will deal with options for handling the reprocessed uranium arising from the electrochemical reprocessing of LWR and fast reactor oxide or metallic fuels.

This distinction of whether fast reactor or LWR fuel is being electrochemically reprocessed is very important. Much larger quantities of uranium must be handled from the electrochemical processing of spent LWR fuel. It will likely be a few hundred years before enough fast reactors exist that could readily use the electrochemically-derived reprocessed uranium from LWR spent fuel as make-up

material for fast reactor metal fuel refabrication or for fast reactor mixed oxide uranium-diluent. For this scenario, it is likely that thousands of metric tons of highly contaminated uranium-metal would be generated from an electrochemical process that takes UOX spent fuel as the feed form, reduces it to metal, and produces all metal separated products.

- The price of natural uranium, U_3O_8 to UF_6 conversion, and uranium enrichment all affect the economics of reprocessed uranium use. If these prices are high, as they are now, the attractiveness of recycling (purifying, reconverting, reenriching, and refabricating reprocessed uranium into UOX fuel) versus reprocessed uranium storage or disposal is enhanced.

2012 AFC-CBD Update Introduction. Since the 2009 AFC-CBR no new data on the economics of RU disposition from pyroprocessing (electrochemical reprocessing) has been obtained. This is not surprising, since pyroprocessing is envisioned more for fast reactor integral fuel recycling than for LWR fuel recycling. For high fast reactor conversion factors little or no uranium would arise from the internal recycle loop for metal fuel reprocessing/refabrication. For these "burn" or "breed" systems uranium would actually be required as a make-up feed material. If pyroprocessing were to be used for spent LWR fuel reprocessing, large quantities of impure metallic U would be produced. For fast reactors operating in a breeder mode, a portion of the LWR-RU arising from electrochemical LWR fuel reprocessing could be used as blanket material for Pu production (but probably requiring remote refabrication). If the FRs only operate at significantly lower conversion ratios there is little or no need for this electrochemically recovered LWR uranium. As Module K3 in the 2009 AFC-CBR explains, the handling and disposal costs for this actinide and fission product contaminated material (essentially a waste) could be high

K3-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

For a typical electrochemical option, reprocessed uranium in the form of a metal is separated from fission products and other actinides in an early step in the separations part of the reprocessing facility. According to Michaels and Welch (1993), the best option for safe storage is to first cast the separated uranium-metal into 180 kgU cylindrical ingots and store them in cans with stainless steel jackets. This jacketing step prevents moist air from oxidizing the uranium metal and producing fines which can become airborne or even burn. Because of the radioactivity from unseparated fission products and higher actinides, this ingoting/canning operation would likely have to take place in the remote handling part of the reprocessing plant. After this step there are several options for use or disposition of this reprocessed uranium product:

- **Long-Term but Temporary Storage**. It is likely that electrochemically-derived reprocessed uranium would not be immediately "thrown away," but saved for the possible future uses, some of which may be many decades away when fast reactor fuel cycles begin to dominate the nuclear enterprise. Among these future uses are the following:
  - If the electrochemically reprocessed uranium is derived from LWR spent fuel, it will be produced in large quantities. It is possible to save it for eventual recycle into new LWR or higher-enrichment fast reactor startup fuel as described below. Tens of years of storage would probably be required.
  - The reprocessed uranium can be saved for makeup uranium for refabrication of metal fuel for a fast reactor fuel cycle. It can also be used to make mixed oxide fuel for oxide-based fast reactor fuel cycles. Since introduction and widespread use of fast reactors could take a few hundred years, any LWR-derived electrochemically reprocessed uranium would have to be stored for that amount of time. Reprocessed uranium from fast reactor spent fuel electrochemical processing could be reintroduced in less time and would require fewer years of storage. The quantities of

reprocessed uranium produced by fast reactor electrochemical processing are smaller than for LWR spent fuel electrochemical processing.

- **Recycle**. The reprocessed uranium could be cleaned up, converted to UF_6, and reenriched. The enriched uranium could be used for LWRs or for highly enriched uranium startup of fast reactors. Many tens of years of storage would be required if there is no immediate need for uranium recycle fuel. The nature and cost of the required storage facility will depend on the radiation level at the surface of the U-metal ingots and the amount of worker protection which is needed during their emplacement and long-term surveillance.

- **Permanent Geologic Disposal**. The reprocessed uranium material, which is less radioactive than high-level waste or spent fuel, but a lot more radioactive than aqueously-derived reprocessed uranium, can be packaged for permanent geological disposal in a matter somewhat akin to Greater-Than-Class-C waste. Stainless jacketed metal ingots directly from the electrochemical plant or storage facility are not an ideal permanent disposal form, because the relatively thin stainless steel jacket may corrode away in several decades and expose the uranium-metal to water or moist air in a repository. U_3O_8 is a more chemically stable form, however, robust packaging or grouting of the powder would be needed to reduce the possibility of fines and prevent eventual leaching of radionuclides. A robust waste container would be needed to encase the grouted mass. Near-surface burial of low-level waste-type packages, such as is proposed for enrichment tails DU_3O_8 (Module K1), would not be permissible. A deep or tunneled geologic repository type environment, like Yucca Mountain, would be more appropriate, and the heat load associated with this material would be orders of magnitude smaller than for high-level waste or spent fuel. U-234 and some transuranic isotopes would present the longest range radiotoxicity hazard. U-232 daughters and most fission products remain a problem for only a few dozen years. Preparation of the packages for repository emplacement is likely to be a remote-handling operation.

- **Preparation for Recycle as UOX Fuel for LWRs or Initial Fast Reactor Cores**. The reprocessed uranium ingot can be dejacketed and converted to an oxidized form, such as UO_3, by controlled burning. This powder is suitable for fluorination/purification to reprocessed UF_6. (Fluorination itself can be a dry route to U-purification, because fission product and higher actinide fluorides are less volatile than UF_6.) The reprocessed UF_6 can undergo reenrichment to a U-235 level somewhat above that required for "virgin" LWR UOX fuel derived from natural uranium. The extra enrichment is needed to compensate for the neutron absorption by U-236. The reprocessed UF_6 can be refabricated into LWR reprocessed UOX in a conventional reprocessing plant if the small amount of U-232 remaining after purification is separated out in the enrichment process. This option is discussed in greater detail in a special section of Module D1-1 (LWR UO_2 Fuel Fabrication) and in Module K2. The reprocessed UF_6 can also be taken to higher enrichment levels (>15% U-235) and the enriched product fabricated into fast reactor fuel (Module D1-4) for startup of the first fast reactors. This is an especially good option if not enough plutonium is available for the initial fast reactor cores.

K3-3. PICTURES AND DIAGRAMS

Figure K3-1 shows schematically the possible disposition paths for reprocessed uranium resulting from electrochemical fuel reprocessing. The paths were described in the subsection above.
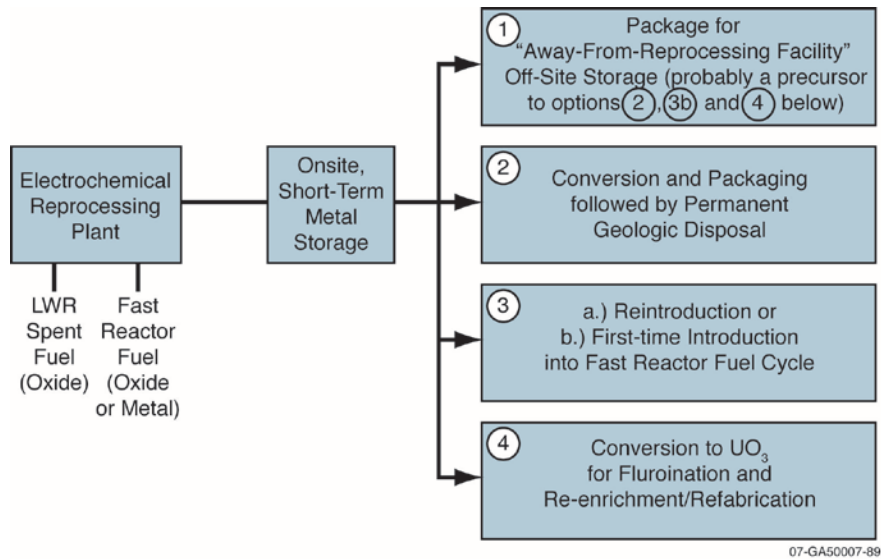
Figure K3-1. Options for reprocessed uranium arising from electrochemical reprocessing of LWR and fast reactor fuels.

K3-4. MODULE INTERFACES

Front-end interface. The electrochemical spent fuel reprocessing plant (Module F2/D2) represents the front end interface. The analyst should make sure the reprocessed uranium ingot casting and jacketing operation is included in the $/kgHM cost of the reprocessing steps, since this remote-handling step must be undertaken at the reprocessing complex. Transportation of the metal ingots to the storage location would likely require special overpacks or containers, but could probably be handled by a commercial carrier. This transportation/packaging cost should be assigned to this module (K3) and is expected to be very small.

Back-end interface. The electrochemically-derived reprocessed uranium disposal options above should not be confused with those in Modules G3 (LLW Conditioning, Storage, and Packaging), J (Near Surface Disposal), or L (Geologic Repository). The costs for the Module K-3 permanent disposal option take the material all the way to final disposal and G3, J, or L costs should not be superimposed upon these.

If recycle is warranted, the costs for this Module K3 step include conversion of the metal to an oxide and fluorination of this oxide all the way to reprocessed UF_6. If the uranium-metal feed has accumulated U-232 decay daughters, the fluorination process can be designed to remove them, thus reducing the radioactivity level in the enrichment and fuel fabrication facilities. Costs for enrichment and fuel refabrication are covered in Modules C1 (Uranium Enrichment), D1-1 (LWR UO_2 Fuel Fabrication), and D1-4 (Ceramic Pelletized Fast Reactor Fuel). Use of even cleaned-up reprocessed uranium is anticipated to raise these separative work unit and fabrication costs by up to 20% above that for virgin feed materials.

K3-5. SCALING CONSIDERATIONS

No data are available. Any reprocessed uranium handling/conversion facilities are likely to be located on the reprocessing plant site, hence sizing might be similar to that for Module F2/D2.

K3-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

The unit cost figure of merit of interest (and its value) for this step depends on which of the above options is chosen. Each option will be separately discussed below.

Temporary Storage. Temporary storage costs will depend on how long the material is stored. An owner of separated reprocessed uranium metal, the most likely reprocessed uranium storage form, will save it in monitored retrievable storage until the price of natural U_3O_8 rises to the point that recycling of reprocessed uranium as LWR for higher enrichment fast reactor fuel is economically beneficial, or the owner will arrange for its permanent disposal. A 1993 Oak Ridge National Laboratory report (Michaels and Welch 1993), prepared to support the Department of Energy Office of Nuclear Energy, Science, and Technology (DOE/NE) Advanced Liquid Metal Reactor program at that time, suggests that the more radioactive material, requiring remote-handling (a container surface radioactivity of 200 mrem/hr or more), can be bulk stored in vaults at a capital cost of $13/kgU in today's (2007) dollars ($9/kgU in 1993 dollars). In light of other radioactive material storage capital costs, such as those for transuranic waste storage and for spent fuel casks, this unit cost is felt to be possible, but optimistic. A value of $20/kgU is felt to be more appropriate given today's more stringent regulations and building standards (which are still evolving). The report also suggests that at a storage fill rate of ~2,000 MTU/yr, the facility would incur operational cost of $5 million/yr (2007 dollars) during filling and $1.5 million/yr (2007 dollars) during surveillance only. These operations costs seem to be reasonable for what is only a logistical/surveillance task, and are the same as those for the less radioactive aqueous reprocessing–derived reprocessed uranium. The problem is that this material may have to be stored for many decades before the reprocessed uranium can be used in fast reactor cycles. Any utility considering recycle in LWRs is likely to want to start with reprocessed uranium from aqueous reprocessing because of its lower radioactivity and lower handling costs, hence, electrochemically-derived reprocessed uranium would be used lastly for this purpose. A vault-type storage facility holding 80,000 MTU would cost $1.6 billion and if it operated for 300 years would accumulate $750 million in operations costs. The total unit cost would amount to around $30/kgU. If multiple centuries of storage are required, unit costs could rise into the hundreds of dollars per kgU (Michaels and Welch 1993).

Permanent Geologic Disposal. The 1993 Oak Ridge National Laboratory report (Michaels and Welch 1993) suggests that reprocessed U_3O_8 could be disposed in a deep or tunnel-type geologic repository for $72/kgU in 2007 dollars ($53/kgU in 1993 dollars). This would presumably include the waste package and transportation from the storage location. It does not include the cost of converting the uranium-metal ingots to U_3O_8. The 1993 ORNL report suggests a cost of $7/kgU (2007 dollars) for this conversion; however, this seems low in light of the radioactivity level of the metal feed. A unit cost of $21/kgU seems more realistic and would include transfer of the U_3O_8 into the new waste container. This would give an overall cost of $93/kgU for permanent geologic disposal. For comparison, costs of $15/kgU (2007 dollars) ($11/kgU in 1993 dollars) were given for geologic disposal of the less radioactive DU_3O_8 derived from uranium enrichment operations and $72/kgU for aqueous reprocessing-derived reprocessed U_3O_8. (Note: Expensive deep or tunnel disposition of enrichment-derived tails DU_3O_8 will hopefully never be necessary. See Module K-1 for discussion of this material and its disposition paths and costs. Module K-2 discusses reprocessed uranium from aqueous reprocessing.)

Preparation for Recycle as LWR Fuel. The cost of the conversion/processing service required before enrichment will depend on how long the material has been stored since reprocessing and the amounts of fission product and transuranic contaminants in the U-metal starting material. It is likely that a "dry" volatility-type fluorination process can be used to make UF_6 and at the same time separate out the small amounts of fission products, TRUs, and U-232 daughters. According to the 1993 ORNL report, "new" recently-separated uranium metal electrochemical processing product can be converted to U_3O_8 for $7/kgU (2007 dollars). In the subsection above, this number was revised to $21/kgU. This unit cost is probably too low for converting U-metal to UF_6, which is a more complex process. The 1993 ORNL

report suggests a unit cost of \$42/kgU (2007 dollars). To calculate the total UOX fuel cost, enrichment and refabrication costs would need to be added (Modules C1 and D1-1). This option is further discussed in Modules D1-1 and K2.

Reprocessed UO_2 would make an excellent fuel for CANDU reactors. No additional enrichment would be needed, since the U-235 content of reprocessed uranium fits the requirements of CANDU designs. This cost is discussed in Module K2.

Use as a Diluent for Contact-Handled MOX Fuel. As for UOX recycle above, the unit cost to make a material suitable to refabrication into contact-handled fuel would depend on how long it has been since the uranium product was separated during reprocessing (the U-232 daughter problem) and how bad the feed material is contaminated with fission products. Transuranic contamination would be less important, because glovebox operations can accommodate most plutonium and neptunium isotopes. If the time is very short and fission product concentrations low, a fuel grade, "moxable" UO_2 powder could be prepared from uranium-metal for around \$42/kgU. If old, daughter-laden feed material is used or fission product concentrations too high, another \$42/kgU would be required for aqueous polishing prior to powder preparation. If these numbers are used in an analysis, care should be taken to remove the part of the unit mixed oxide fabrication cost (Module D1-2) that comprises the depleted U_3O_8 to "moxable" depleted UO_2 powder step. Around \$30/kgHM of the overall mixed oxide fabrication cost is attributable to this operation if the mixed oxide plant receives enrichment plant derived depleted UF_6 or depleted U_3O_8 as the PuO_2 diluent.

K3-7. DATA LIMITATIONS

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

1. Because of U-236 buildup, it is likely that reprocessed UOX could undergo at most two recycles. If a highly selective method for uranium enrichment became available (one that could selectively remove U-236) more recycles of UOX would become feasible.

2. The problem of large amounts of contaminated reprocessed uranium is one reason that electrochemical processing is better suited for the internal recycle of fast reactor fuel and not the large scale reprocessing of spent LWR fuels.

In general, the reprocessed uranium disposition step of the electrochemical fuel cycle can be placed in the "demonstration required" category of technology readiness. Uranium ore prices will help dictate when and how reprocessed uranium is dispositioned.

K3-8. COST SUMMARIES

The module cost information in the 2012 AFC-CBD is summarized in the What-It-Takes (WIT) cost summary in Table K3-1. The summary shows the reference cost basis (constant year \$U.S.), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table K3-1. Cost summary table for reprocessed uranium disposition options.

What-It-Takes (WIT) Table (2012$)				
Reference Cost(s) Based on Reference Capacity	Reference Cost Contingency (+/- %)	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Nominal Cost)
SS-clad U-metal ingots: 300-year Storage" $20/Kg U for 80,000 MTU/yr Storage Capacity ($1,600M). Annual costs of $1.5M to $5M/yr	In unit cost, amount unknown, but not felt to cover all risks.	$25/kgU for tens of years of storage	$100+/kgU if centuries of temporary retrievable storage required.	$31/kgU for 300-yr storage
Electrochemically-derived reprocessed U_3O_8 Permanent Geologic Repository Disposal	In unit cost, amount is unknown	$75/kgU if contamination level only marginally above that of aqueously-derived reprocessed uranium	$150/kgU if sitting and regulatory difficulties arise	$93/kgU including metal to U_3O_8 conversion, repackaging, transportation, emplacement, and perpetual surveillance
Preparation for UOX recycle: U-Metal product to UF6 (including fluoride volatility removal of fission product, higher actinides, & U-232 daughters)	In unit cost, amount is unknown	$30/kgU	$60/kgU	$42/kgU
Internal reuse in fast reactor electrochemical fuel cycle		Included in fuel fabrication cost Module F2/D2	Included in fuel fabrication cost Module F2/D2	Included in fuel fabrication cost Module F2/D2
UO_2 diluent preparation for contact-handled MOX fuel		$30/kgU	$60/kgU	$42/kgU including aqueous polishing and conversion to fuel grade UO_2 powder

Table K3-2 presents the same data escalated to 2015.

Table K3-2. 2015$ updated "What-It-Takes" Table (2015 $).

REPU Fuel Cycle Step	Low	Mode	Mean	High
REPU Storage	$26 /kgU	$33/kgU	$55/kgU	$105/kgU
Perm Geologic Disposal	$79/kgU	$98/kgU	$112/kgU	$158/kgU
U-metal to UF_6 conv	$32/kgU	$44/kgU	$46/kgU	$63/kgU
Conv to Moxable UO_2	$32/kgU	$44/kgU	$46/kgU	$63/kgU

Table K3-3 presents the same data to year 2017 constant dollars. A factor of 1.14 was used to escalate from 2012 dollars.

Table K3-3. 2017$ updated "What-It-Takes" Table (2017$).

REPU Fuel Cycle Step	Low	Mode	Mean	High
REPU Storage	$28.5/kgU	$35.3/kgU	$62.7/kgU	$114/kgU
Perm Geologic Disposal	$85.5/kgU	$106/kgU	$127.7/kgU	$171/kgU
U-metal to UF_6 conv	$34.2/kgU	$47.9/kgU	$52.4/kgU	$68.4/kgU
Conv to Moxable UO_2	$34.2/kgU	$47.9/kgU	$52.4/kgU	$68.4/kgU

The triangular distributions are based on the costs in the WIT Table is shown in Figure K3-2.

Module K3

300 yr Storage of E-Chem Reprocessed U Product

(Yr 2017$)

Relative
Frequency

mean = expected value= 62.7

mode=35.3

low

high

28.5 35.3   114

Unit Cost ($/kgU)

Module K3

Permanent Geologic Disposal of E-Chem Reprocessed U Product

(Yr 2017$)

("Old" material has significant U-232 build-in)

Relative
Frequency

mode=106

mean = 127.7

low

high

85.5   98.1   171

Unit Cost ($/kgU)

Module K3

Conversion of E-Chem Repr Product to UF6

(Yr 2017$)

Relative
Frequency

mode=47.9   mean = expected value= 52.4

low   high

34.2   47.9   68.4

Unit Cost ($/kgDU)

Module K3
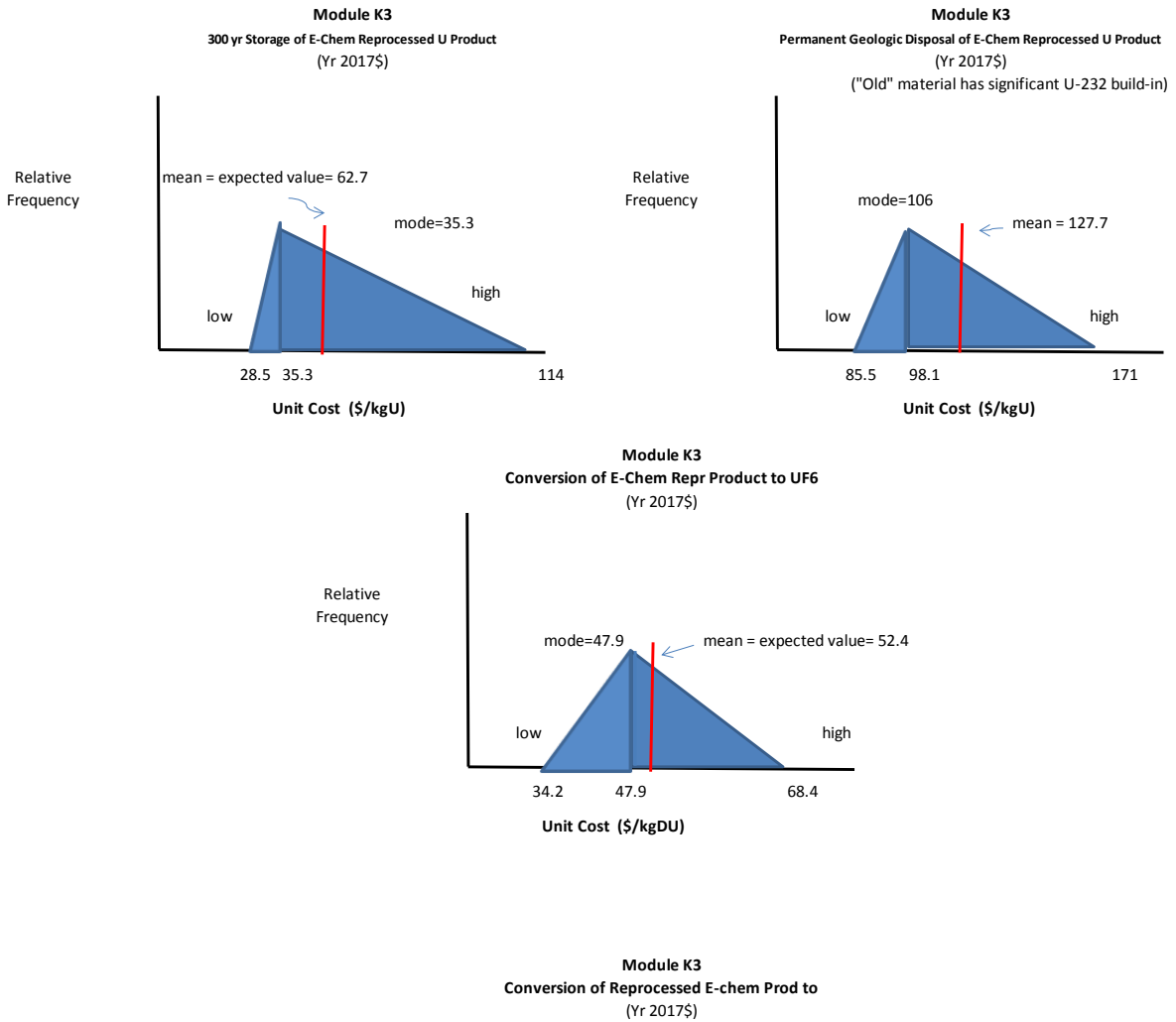
Conversion of Reprocessed E-chem Prod to

(Yr 2017$)

Figure K3-2. Electrochemical reprocessed U disposition estimated cost frequency distributions.

K3-9. RESULTS FROM SENSITIVITY AND UNCERTAINTY ANALYSIS

Due to lack of detailed process/cost data no such calculations were performed.

K3-10. REFERENCES

Michaels, G. and T. Welch, 1993, *Evaluation of Disposition Options for Reprocessed Uranium*, ORNL/TM-12326, Oak Ridge National Laboratory, February 1993.