

Advanced Fuel Cycle Cost Basis Report: Supporting Document 7 Presentation: Du and RU Disposal Costs

**Nuclear Fuel Cycle and
Supply Chain**

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**Supporting Document 7 Presentation: Du and RU Disposal Costs
Fuel Fabrication Preface to FY 2021 Updates to the Supporting Documents**

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ACKNOWLEDGEMENT

This latest version of the *Supporting Document 7 Presentation: Du and RU Disposal Costs* is the cumulative effort of many authors who have contributed to the *Advanced Fuel Cycle Cost Basis Report*. All the authors, including the four primary authors, 15 contributing authors, 12 contributors acknowledged, and the many other unacknowledged contributors from the 2017 report, have contributed various amounts to developing and writing this module prior to this current revision. Unfortunately, there is no history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. Jason Hansen (Idaho National Laboratory, jason.hansen@inl.gov) and Edward Hoffman (Argonne National Laboratory, ehoffman@anl.gov) can be contacted with any questions regarding this document.

**Supporting Document 7 Presentation: Du and RU Disposal Costs
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DU and RU Disposal Costs

Erich Schneider, University of Texas,
Austin, TX

Kent Williams, Consultant, Knoxville, TN
April 2015

Present Situation

- Worldwide DU and RU in various chemical forms are some of the largest legacy products of the nuclear industry (defense & power) in both mass and volume
 - DU: > 10E+6 MTU (from large scale enrichment)
 - RU: > 10E+5 MTU (from large scale reprocessing)
- Chemical forms include U metal or alloy, UF₆, UO₂, UO₃, U₃O₈, and UF₄
- Most of this material is now in above ground storage
- Due to chemical stability and low water solubility oxides are the preferred form for safe storage and ultimate disposal

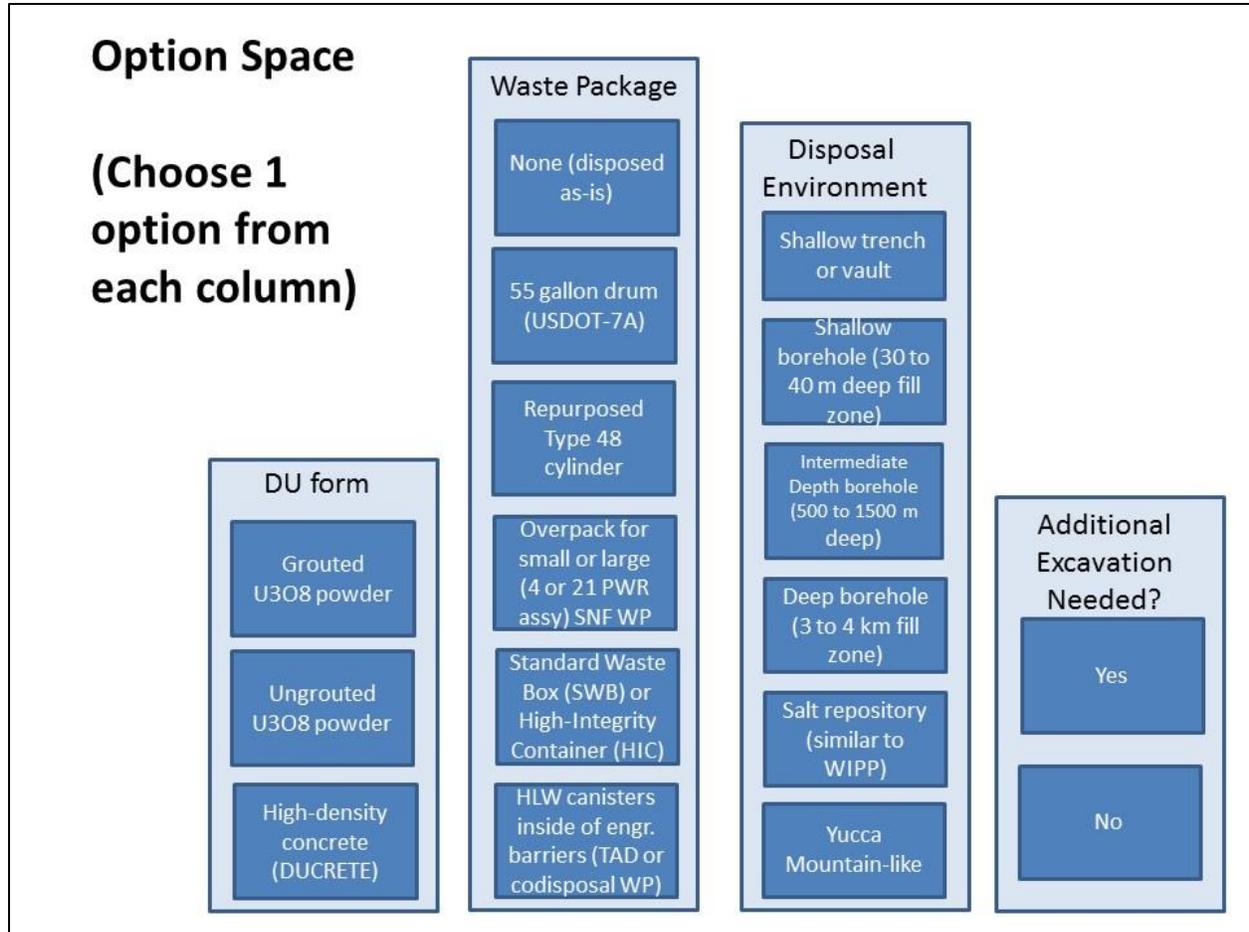
Long term U disposal in large amounts presents more of a potential radioactivity problem than its conversion and temporary storage

- Now a near term problem with freshly-mined uranium ore, radon emanation will eventually be a long-term problem for both DU and RU dispositioned in large quantities at a specific location
 - Separated* Uranium's specific activity increases with time (mining/milling, enrichment, and reprocessing remove non-U daughters, hence time=0 starts after these ops)
 - Millions of years, however, to reach secular equilibrium
 - Any shallow burial essentially results in a "uranium mine" with U concentration in the inherent dense solid medium of over 60%
 - Planned disposal of DU and RU forms in shallow LLW disposal sites meeting some institutional resistance.
 - Large quantities may require expansion of LLW disposal land area at some sites

***U-ore processing/milling, uranium enrichment, and spent fuel reprocessing physically or chemically separate uranium from non-uranium decay daughters and other non-U elements.**

We will first consider DU

- Two sources of DU
 - Enrichment process “tails” ($< 0.711\%$ U-235) collected as DUF6 in large steel cylinders
 - Some facilities convert this to more stable U3O8
 - “Tails” has been produced since 1945
 - Most tails is “virgin”, i.e. it arises from unirradiated U fed to uranium enrichment plants and is free of trace fission products or transuranics
 - Tails with significant FPs or TRUs therein would be treated like RU.
 - Irradiation of LEU driver fuel or Natural or depleted U blankets/targets can result in U-235 assays less than 0.711% U-235 in recovered reprocessing U product, depending on burnup
 - This separated low-assay product is sometimes re-enriched
 - This material is really reprocessed U (RU) and will be considered in second part of this presentation



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Cases considered in this study

ID	DU Form	Waste Package	Disposal Environment	Additional Excavation?	AFCBR module designator
1	Ungouted	Drum, cylinder, or SWB	Shallow Trench or Vault	Yes	K1, J, L2 alts. 4 and 5
2	DUCRETE	Overpack for small or large WP	Yucca Mountain-like	No	--
3a	Ungouted	55 gallon drum or Type 48 cylinder	Yucca Mountain-like	No	K2
3b	Ungouted	55 gallon drum or Type 48 cylinder	Yucca Mountain-like	Yes	--
3c	Ungouted or grouted	HLW canisters in co-disposal WP	Yucca Mountain-like	Yes	L1
4a	Ungouted	Drum, cylinder	Shallow borehole	Yes	L2 alternative 3
4b	Ungouted	None or equivalent of drum/cylinder	Intermediate depth borehole	Yes	--
4c	Ungouted	None or equivalent of drum/cylinder	Deep borehole	Yes	L1 alternative 7
5	Ungouted	Drum, cylinder, or SWB	Salt repository	Yes	L1 alt. 2, L2 alt. 2

Four DU Waste Forms

Form	Nominal Density [kg/m ³]	Uranium Density [kg/m ³]	Comment
U3O8 Powder	2800 (max packing)	2370 (max packing)	WAC limit at NTS for shallow DU disposal is 2600 kg DU/m ³
Grouted U3O8	~3000	1190	
UF4	3000	2270	May be compatible with certain environments, not considered further here
DUCRETE	5500	3550	Make high-density 'DUAGG' ceramic by sintering U3O8 with silica, alumina

**Most cost studies to date have dealt with DU/RU conversion,
DU/RU storage and possible DU/RU shallow disposal**

- Conversion is the process of producing a safer, “above-ground” storable chemical form from the enrichment plant or reprocessing plant outputs (UF₆ or uranyl nitrate hexahydrate respectively);
 - “Tails cylinder” stored UF₆ to U₃O₈ for DU: conversion now underway in US and France
 - Uranyl Nitrate Hexahydrate solution to UO₃ or U₃O₈ (after LWR-SNF aqueous reprocessing)
 - Uranium metal is likely form from pyroprocessing of metallic fast reactor fuels
- Few studies have considered “deeper” disposal of packaged oxide or metal DU or RU forms
- Advanced Fuel Cost Basis Reports began to do this in 2009 and 2012
- We are revisiting these uranium disposal fuel cycle steps again and looking at some new options!

Current unit cost values in *Advanced Fuel Cycle Cost Basis Report (2012 Update)*

- Geologic Disposal* of Packaged DU308:

– Low	2 \$/kgDU	Most favorable estimate found in literature
– Most Likely	4 \$/kgDU	High end of private LLW site estimates
– High	22 \$/kgDU	Avg of DOD ThO2 & anti-nuke “deep disposition” estimate

*Deconversion/packaging costs not included

Packaging: 55 gallon drums, standard waste boxes (SWBs), high-integrity containers HICs

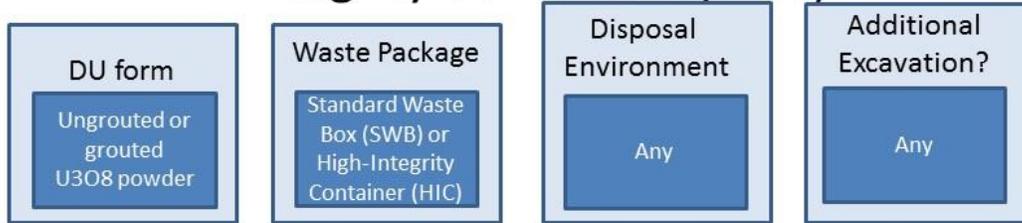
- Cheapest disposal packaging options would be none at all (e.g. pour powder directly into a borehole) or reuse of DUF6 cylinders
- A 55-gal carbon steel drum (~\$100) would contain 540 kg U3O8 (Hightower 2000).
 - Unit cost : **\$0.2/kg DU**
- DU may be disposed in containers typically used for other LLW or GTCC waste rather than 55-gallon drums or surplus Type 48 cylinders
 - LLW at the NNS is typically disposed in Type B-25 SWBs
- A high-integrity container is designed to meet the structural stability requirements of 10 CFR §61.56
 - 10 CFR §61.56 says that the stability of waste be provided by the waste form itself, by processing the waste into a stable form, or by placing the waste into a container that provides stability after disposal
 - HICs are required to withstand 30 foot drop onto an unyielding surface and designed to contain waste for 300 years
- Commercially-approved HICs include
 - NUKEM Nuclear Technologies NUHIC-55
 - SEG Enduro Pak HDPE HIC
 - SEG SQ113 Concrete HIC



High Integrity Container of Class A LLRW being placed in a cylindrical disposal vault.

Reference: Hightower, J.R. and Trabalka, J.R., "Depleted Uranium Storage and Disposal Trade Study," ORNL/TM-2000/10, 2000.

Use of Standard Waste Boxes (SWBs) or High-Integrity Containers (HICs)



- The Container Products Corporation B-25 will be considered as a reference SWB
 - Cost: \$2,500
 - Internal volume: 2.55 m³
 - Maximum load: 2700 kg
- Given the density of DU3O8, the maximum load is limiting, so 2700 kg DU3O8 (2290 kg DU) can be loaded per B-25
- Therefore using this SWB for disposal would add $\$2,500/2,290 = \$1.1/\text{kg DU}$
- The Enviralloy EA-50C will be considered as a reference HIC
 - Cost: \$50,000
 - Internal volume: 1.19m³
 - Maximum load: 1900 kg
- Given the density of DU3O8, the maximum load is limiting, so 1900 kg DU3O8 (1610 kg DU) can be loaded per HIC
- Therefore using this HIC for disposal would add $\$50,000/1610 = \$31/\text{kg DU}$

Sources for B-25 costs and dimensions/payload: <http://c-p-c.net/b-25-waste-containers.asp> and Arkansas Nuclear One Decommissioning Cost Analysis, Document E11-1605-002.

1. 'Shallow' Disposal at LLW Facility



- Was considered in Modules K1 (and indirectly J and L2)
- Module K1 presented 3 cost estimates for trench/vault disposal which ranged from \$1.5-\$4/kg DU
- One of these estimates was developed for the Waste Control Specialists (WCS) facility in Texas
 - WCS is now authorized to dispose large quantities of depleted uranium in concentrations greater than 10 nCi/gram
 - DU will be encased in concrete at a depth ca. 100 feet
 - More on the WCS facility later in the presentation
 - No new cost data specifically applicable to WCS was found

Shallow Disposal of DU at LLW Facility – cost from Module J of 2009 CBR

- Module J of the 2009 CBR featured a bottom-up assessment of LLW disposal at a NNSS-like facility
 - it was developed with non-DU LLW in mind, but aside from packaging costs (discussed earlier) it is applicable to DU co-disposal and provides another unit disposal cost estimate

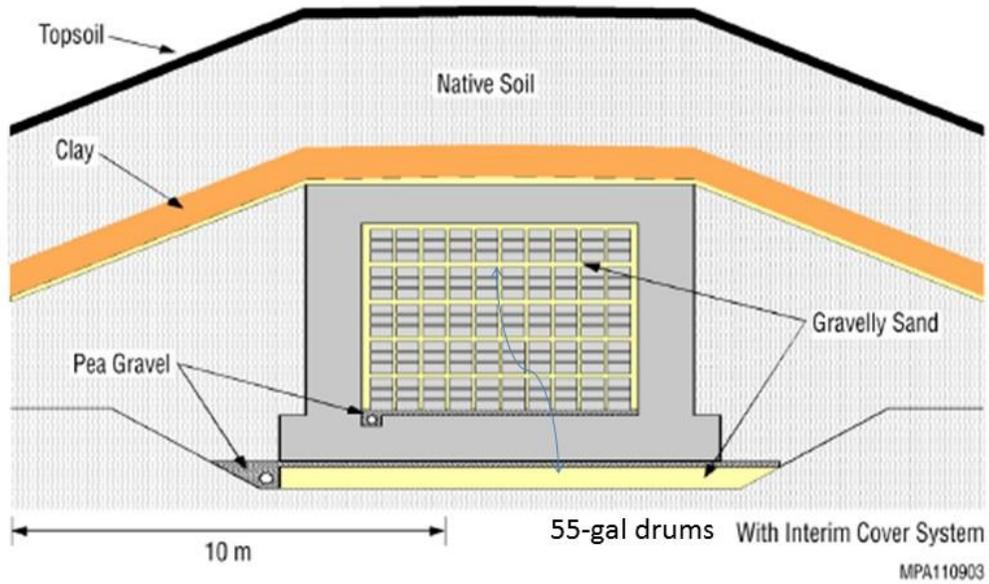


Shallow Disposal of DU at LLW Facility – cost from Module J of 2009 CBR and comparison to Module K1 of 2012 CBR

- From Module J:
 - Unit disposal cost per volume of waste: \$1,250/m³ (nominal)
 - Volume of B-25 SWB: 2.55 m³
 - Mass of DU loaded per SWB: 2,290 kg DU
 - Unit disposal cost: $1,250 \times 2.55 / 2,290 = \$1.4/\text{kg DU}$ (\$1.5/kg DU in 2011 dollars)
 - high end Module J unit disposal cost of \$2,500/m³ corresponds to \$3/kg DU in 2011 dollars
 - Adding packaging costs of \$1.1/kg DU brings the total for shallow DU disposal at an NNSS-like facility to **\$2.6-\$4.1/kg DU**, much the same as the **\$1.5-\$4/kg DU** from the three estimates used to develop the low and nominal cost estimates in Module K1

Shallow Burial in Vaults from Module L2 option 5:

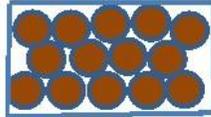
Specially-constructed vaults have been considered for DOE-EM GTCC waste and could be adapted to DU308



Consider this vault option for DU3O8-filled Type-48 steel cylinders

- Module L-2 of AFC-CBD Update (Geologic Disposal: GTCC) gives a unit cost of \$4333/m³ of vault space (for cylindrical stacked drums)
- Stacked 48-G cylinders could provide effective vault volume utilization of 80%, i.e. 80% of vault volume is dispositioned bulk U3O8 powder

Assume that instead of 55-gallon drums stacked vertically 4 high, that Type 48 U3O8-filled "tails" cylinders could be laid horizontally side to side and stacked vertically up to 3 high in the vault.



- Adjusted Unit cost would then be ~\$5420/m³ of powder
- Unit cost depends on bulk density (1.8 to 2.6 MT/m³):

Density	\$/kg DU3O8	\$/kg DU
2.6	2.08	2.46
2.3	2.35	2.78
1.8	3.01	3.55

- This falls in mid-range of better-known "shallow" burial unit costs and agrees with the results derived from Modules K1 and J and shown above
 - But the more complex vault volumetric cost estimate might be low.

Shallow disposal at LLW facility: experience disposing thorium nitrate at NNSS

- 1,290 tonnes of $\text{Th}(\text{NO}_3)_4 \cdot 5\text{H}_2\text{O}$ (not an oxidizer) were disposed at the NNSS in the early 2000s
 - Th was inside 55 gallon drums in cargo containers similar to the B-25
- Cost of this effort was \$15M, translating to **\$14.5/kg Th** in 2012 dollars



Figures and data from: Hermes, W., "Removing the Source Term – Thorium Nitrate Disposal at the Nevada Test Site," 2007 HPS Midyear Topical Meeting.

Shallow disposal at LLW facility: experience disposing thorium nitrate at NNSS

- Why is this cost nearly an order of magnitude higher than the estimated cost of shallow burial of DU?
 - Cost includes transportation and packaging: some 12% of drums were found to be pressurized, needing venting w/ filtration
 - Project was around two orders of magnitude smaller in scale than DU disposal effort
 - Bulk density (1.9 g/cm^3) and Th mass fraction of material lower than density and U mass fraction in DU308
 - Disposition took place in a trench at Area 5: total depth of cover needed to meet 1000-yr ^{222}Rn (from ^{230}Th decay) limits was some 6 meters, so a custom trench had to be dug at Area 5



Figures and data from: Hermes, W., "Removing the Source Term - Thorium Nitrate Disposal at the Nevada Test Site," 2007 HPS Midyear Topical Meeting.

Waste Control Specialists

- WCS operates the only commercial facility in the U.S. licensed (in the past 30 years) to dispose of Class A, B and C LLW and Mixed LLW
 - It is the site for the Texas Low-Level Radioactive Waste Disposal Compact facility for commercial LLRW and the Federal Waste Facility for waste from DOE
 - WCS has contracts in place with most of the nuclear power plants in the U.S. and a nationwide contract with DOE that can be used by DOE or its contractors.
- The WCS facility sits atop a formation of 600 feet of impermeable red-bed clay

Source: WCS press release, February 2015

WCS facilities



NRC and TCEQ Regulations

- Texas is an Agreement State, so licensing of the WCS facility is delegated by NRC to the TCEQ (Texas Commission on Environmental Quality)
- As of August 2014, WCS is authorized to dispose of DU
 - WCS is actively seeking to expand its TCEQ license to dispose GTCC wastes
 - WCS also plans to submit license application for ISFSI to NRC by April 2016 (evidently this must go through the NRC)
- TCEQ regulations for GTCC and GTCC-like LLW stipulate that dose to a member of the public remain below 25 mrem/yr and to an inadvertent intruder below 500 mrem/yr for 1,000 years or until peak dose is reached, whichever is longer
- GTCC waste would be disposed and grouted inside a so-called 'Modular Concrete Canister'

** <http://pbadupws.nrc.gov/docs/ML1503/ML15034A195.pdf>

Modular Concrete Canister

A MCC is approximately 3 meters high and 2 feet in diameter. It weighs approx. 4.5 tonnes when filled with grouted irradiated hardware (or other GTCC). Dose rates are to be < 150 mrem/hr at 30 cm from the MCC surface.



WCS has two facilities

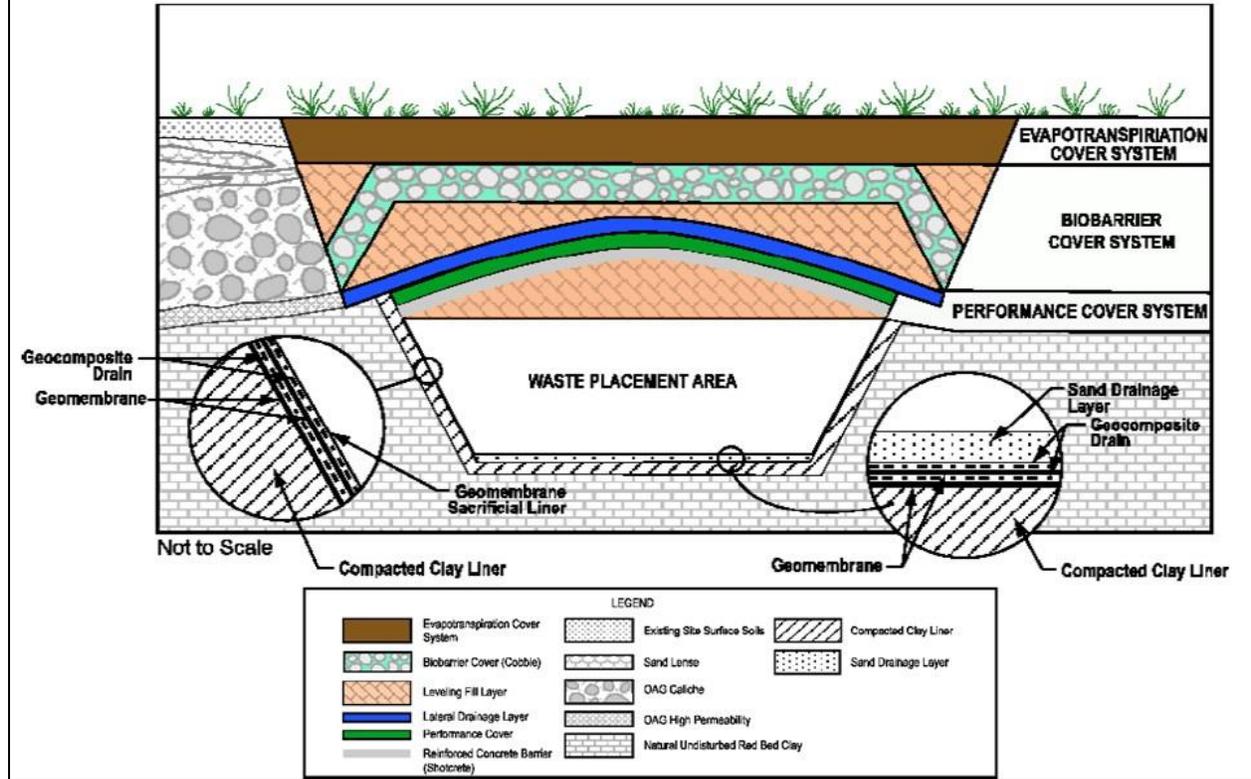
- Compact Waste Disposal Facility (CWF) and Federal Waste Disposal Facility (FWRF)
 - The CWF accepts commercial LLRW (containerized Class A, B, and C)
 - The FWF accepts LLRW and Low Level Mixed Waste (LLMW) that is the responsibility of the Federal government under the LLRW Policy Act, e.g., (Department of Energy (DOE) waste, U.S. Navy vessel decommissioning waste, government atomic weapons Research and Development (R&D), testing or production waste, excluding Greater than Class C).

WCS Federal Waste Facility



Disposition operations will take place 40 meters below grade

WCS post-emplacment cover plan



WCS license provisions from Texas Commission on Environmental Quality (TCEQ)

- Permitted above ground possession of:
 - Any source material not to exceed 30,000 kg
 - SNM not to exceed 350 grams of U-235 (or 200 grams of Pu or U-233)
- Total volume of disposal facilities* increased to 35 million ft³
 - volume of CWF (where civilian DU would likely be emplaced) increased from 2.93 to 9 million ft³ (255,000 m³)
 - total decay corrected radioactivity not to exceed 9.49 MCi (of which 3.89 MCi in the CWF)
 - Disposal of DU is authorized under the TCEQ license as of August 2014
- GTCC waste is still excluded but WCS is actively seeking to amend their license to allow GTCC disposal**

* Compact Waste Disposal Facility plus Federal Waste Disposal Facility.

** <http://pbadupws.nrc.gov/docs/ML1503/ML15034A195.pdf>

DU disposition by WCS

- DU is classified as Class A but increases in radioactivity over time
 - WCS will disposition DU encased in concrete at a depth of more than 100 feet with a cover system that is 30 feet thick
- To obtain the license from TCEQ, WCS had to update its performance assessment to consider disposal of large quantities of DU:
 - “WCS demonstrated that the geological characteristics of WCS’ LLRW disposal facilities are extraordinarily protective and isolate long-lived radionuclides, such as DU, from the biosphere for a period of at least one million years, which was the maximum measurement term of the performance assessment.”*

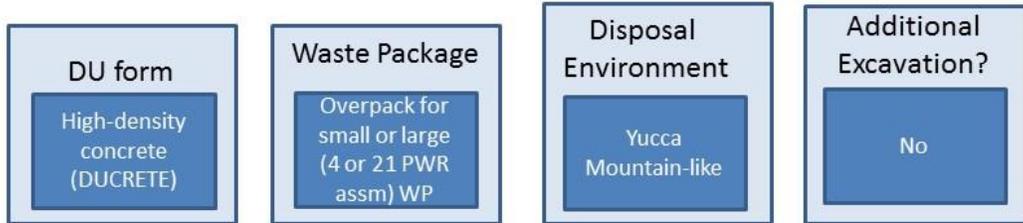
*<http://www.wcstexas.com/2014/license-amendment-enhances-disposal-options/>

DU disposition by WCS

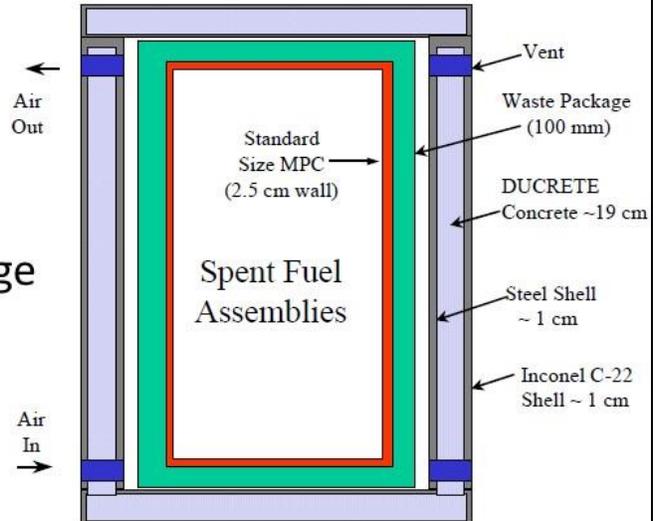
- If converted to oxide with a nominal density of 2800 kg/m³, the 550,000 tDU currently held in the US would occupy a volume of 230,000 m³
 - This represents around 90% of the 255,000 m³ of volume currently authorized by TCEQ
- Checking against activity:
 - The specific activity of ‘fresh’ DU is ca. 15 MBq/kg
 - The peak specific activity of initially pure DU, occurring at around 1 million years, is 170 MBq/kg
 - The activity of the 550,000 tDU at 1 million years would be around 2.5 MCi
 - This represents around 65% of the 3.89 MCi regulatory limit for the CWF
- **Therefore as of August 2014 the WCS facility has been licensed to dispose hundreds of thousands of tonnes of DU**

*<http://www.wise-uranium.org/rup.html>

2. Disposal of DU as DUCRETE (Waste Package Overpack)

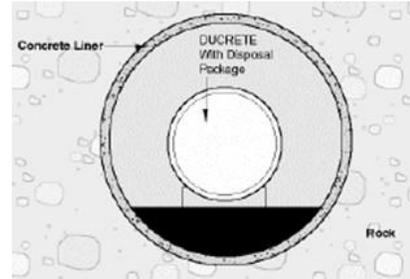


- Considered for YM in the 1990s to early 2000s
- DUCRETE overpack would take the place of conventional waste package overpack
- Emplacement, operations costs were shown to be largely unaffected



DUCRETE fabrication and overpack

- DU must first be deconverted to U3O8 or UO₂ (this cost not included here).
- 'DUAGG' ceramic produced by liquid phase sintering UO₂ with silica and alumina
- DUCRETE is then made by combining DUAGG with Portland cement to produce a very dense (5-6 g/cc) concrete
- DUCRETE overpacks then take the place of conventional overpack



References:

Powell, F.P., "Comparative Economics for DUCRETE Spent Fuel Storage Cask Handling, Transportation and Capital Requirements", INEL-95/0166, 1995.

Quapp, W.J. et al., "DUCRETE: a cost-effective Radiation Shielding Material," Spectrum 2000, Sept 24-28, 2000, Chattanooga, TN.

Quapp, W.J., "DUCRETE Shielding Applications in the Yucca Mountain Repository," WM99, February 28-March 4, 1999.

Disposal of DU as DUCRETE overpack: Costs

- There are two cost components:
 - Fabrication of the DUAGG and DUCRETE, estimated cost (inflated to 2011\$): \$3.0/kg DU (Quapp 2000)
 - Fabrication of the overpacks (inflated to 2011\$): \$1.5/kg DU (Powell 1995)
 - Emplacement cost difference was evaluated in (Powell 1995) to be very small
 - Bottom line: **\$4.5/kg DU** for emplacement of DU in Yucca Mountain like repository (no additional excavation)

3a. Return of DU3O8 to 48Y Containers or 55 Gallon Drums, Emplacement in YM-like Repository



- Likely the simplest DGR option. First step is to deconvert to U3O8
 - The U3O8 powder can be grouted (mixed with cement to form concrete) at minimal cost
 - Grouting can decrease risk of airborne particulate transport
 - (Hightower 2000) showed that grouting increases volume (a negative since underground space is valuable) but is not an effective long-term barrier to radionuclide transport
 - Grouting not considered further

Reference: Hightower, J.R. and Trabalka, J.R., "Depleted Uranium Storage and Disposal Trade Study," ORNL/TM-2000/10, 2000.

Return of DU308 to 48Y Cylinders or 55 Gallon Drums, Emplacement in YM-like Repository

- Cylinders assumed available at no cost but might not be in reusable condition
 - each cylinder has an interior volume of 3.85 m³ and can hold 10,700 kg U308
- Each 55-gal carbon steel drum would contain 540 kg U308
- A YM-like repository would have ample space without additional excavation
 - Total excavated volume of YM is 4.4E6 m³
 - Type 48 cylinders filled with DU from 109,300 tIHM of SNF would occupy 3.9E5 m³ of volume (drums about the same)
 - 109,300 tIHM of SNF was the basis for the 2007 YM TSLCC estimate
 - Therefore, the DU would occupy around 9% of the excavated volume – can envision emplacing it in available space

Costs of emplacement

- First order estimate: from the 2008 YM TSLCC analysis, emplacement operations contribute \$8,050M to the total cost of \$82,500M
 - Strategy envisions emplacing ca. 72,300 Type 48 cylinders which would contain all DU, 660,000 tonnes, produced from fabrication of 109,300 tHM of SNF
 - Mass of a Type 48 cylinder is 2,000 kg (<http://web.ead.anl.gov/uranium/guide/prodhand/sld035.cfm>)
 - Total mass to be emplaced = $72,300 * 2 + 660,000 = 805,000$ tonnes
 - The YM PA called for emplacement of some 17,500 SNF and HLW waste packages with an average mass of ~50 tonnes (DOE 2008, Rechar 2014)
 - Total mass to be emplaced = $17,500 * 50 = 875,000$ tonnes

DOE, "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007," DOE/RW-0591, 2008.
Rechar, R. P. and M. Voegelé, "Evolution of repository and waste package designs for Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste", Reliability Engineering and System Safety, 122, 2014.

Costs of emplacement, cont'd.

- **Very conservatively** assuming that emplacement costs are proportional to mass, DU cylinder emplacement would add $\$8,050 \times (805,000/875,000) = \$7,400\text{M}$ to the TSLCC.
 - Likely to be significantly less costly because of lower radiation field associated with DU containers
- Unit cost of emplacement would be $\$7,400\text{M}/660,000$ tonnes DU = $\$11.2/\text{kg}$ DU (year 2007\$) or **$\$12.2/\text{kg}$ DU**.
 - Aside from deconversion, other costs associated with this strategy are negligible

3b. What if additional excavation is needed?

- Conclusion from the above is that emplacement and disposal of DU in a DGR will be cheap if
 - a DGR for SNF and/or HLW already exists, and
 - no additional excavation is required to make space for the DU.
- Consider that engineering, procurement and construction/excavation costs at YM were \$18,130M for the existing 875,000 tonnes of material to be emplaced
 - Conservatively hypothesize that the additional 805,000 tonnes of material would directly add to these costs

Costs of Additional Excavation



- Excavation would then add $\$18,130 \times (805,000/875,000) = \$16,700\text{M}$ to the TSLCC.
 - This assumes that the additional excavation also complicates licensing, design and surface infrastructure in proportion to the additional mass disposed
- On a per-unit mass basis, this is $\$16,700\text{M}/660,000 \text{ tDU} = \25.3 (year 2007\$) or **$\$27.6/\text{kg DU}$ (year 2011\$)**.
- Adding this to the emplacement cost calculated previously, the unit DU disposal cost would be **$\$39.8/\text{kg DU}$** .
 - This is close to the highest estimates for deep geologic disposal of U3O8 ($\$50/\text{kg U}$) reviewed in AFC CB module K1

3c. What if the DU must be disposed behind SNF-like engineered barriers?

- In the worst case, assume that the DU must be placed behind the same set of engineered barriers as SNF and HLW
- Assume that ungrouted DU is placed inside HLW canisters, and 5 HLW canisters are contained within one co-disposal cask
 - Interior volume of a HLW canister is $\pi/4 * 0.61^2 * 5 = 1.46 \text{ m}^3$.
 - The volume of ungrouted DU308 powder from 660,000 tDU is 278,000 m^3 .
 - A total of 190,000 HLW canisters inside of 38,100 co-disposal waste package would be required

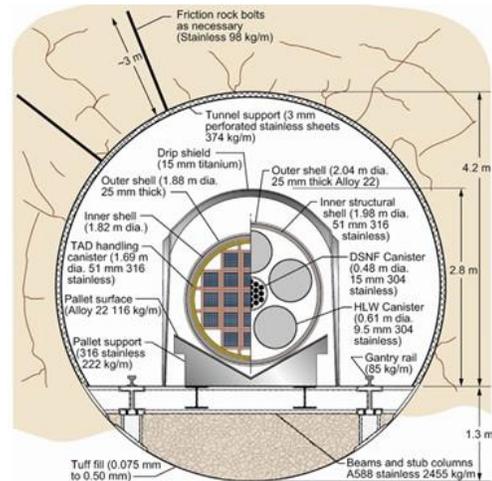
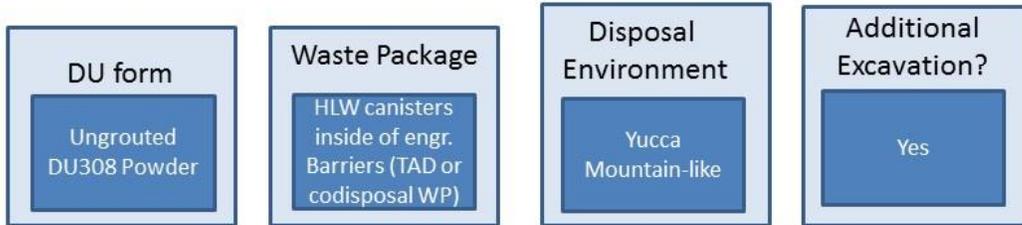


Figure and dimensions from [Rechard 2014].

Worst case: dispose of DU in HLW canisters inside co-disposal WPs

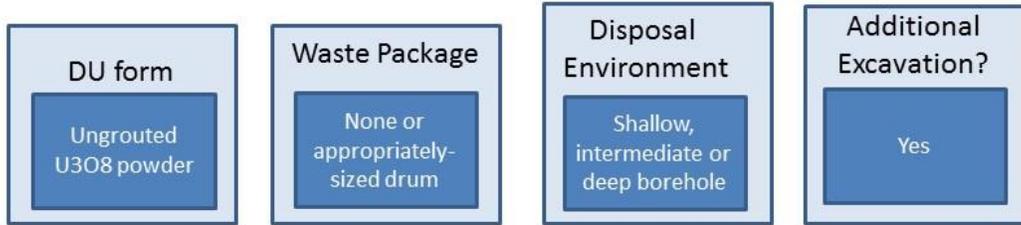


- Cost of waste package and drip shield fabrication for the 17,500 WPs in the 2007 TSLCC assessment was \$12,820M (WPs) plus \$7,630M (drip shields). Performance confirmation and regulatory, infrastructure, management support add \$6,050M; adding these components gives \$26,500M.
 - Conservatively assuming they are proportional to the number of packages, adding 38,100 more packages would increase the cost by $\$26,500 \times (38,100/17,500) = \$57,700\text{M}$.
 - Additional excavation would be needed too since the DU has a larger footprint if emplaced this way rather than in cylinders or drums.
 - Assuming the excavated volume increases in proportion to the number of waste packages, additional excavation cost would be $\$18130\text{M} \times (38,100/17,500) = \$39,500\text{M}$.

Worst case: dispose of DU in HLW canisters inside co-disposal WPs

- Similarly, emplacement costs would increase with the number of packages: $\$8,050\text{M} \times (38,100/17,500) = \$17,500\text{M}$.
- The total additional cost would then be $\$57,700\text{M} + \$39,500\text{M} + \$17,500\text{M} = \$114,800\text{M}$.
- On a per-unit mass basis, this is $\$114,800\text{M}/660,000 \text{ tDU} = \174 (year 2007\$) or **\$189/kg DU (year 2011\$)**.
- Unsurprisingly, this is close to the figure Kent produced for repository disposal of DU by directly scaling the repository disposal module unit costs.
 - At this level, the DU is being disposed under the same engineered barrier system as SNF and HLW. It occupies a large footprint, and additional WP and excavation requirements are enormous
 - This remains somewhat lower than the SNF disposal cost (\$650/kg IHM) because the DU can be packed more densely inside the WPs than the SNF
 - Since there are ca. 6 kg of DU per kg of SNF, though, under this scenario **the DU disposal cost per unit electricity produced would be higher than the SNF disposal cost**

4. Boreholes



- “Depth” and “diameter” of BH will determine cost.
- Module L-2 of 2012 AFC-CBD [GTCC] considers “not-so-deep” 40m deep BHs for GTCC at unit cost of \$2750/m³
 - Shallow Boreholes must be above water table
 - Diameters considered ranged from 1 ft to 12 ft dia.
- This presentation is first look at deeper boreholes for DU3O8 disposition

Borehole (BH) Options

- Borehole drilling technology has benefitted from oil and gas drilling industry, especially deep underwater drilling
- DOE's Sandia National Laboratory has considerable analysis and research on this concept
- BH has been considered for following wastes or materials
 - Plutonium (1996 studies) and (2013 studies)
 - Hanford cesium capsules
 - Spent nuclear fuel (SNF)
 - High Level Waste (HLW)
 - Greater-than-Class C waste (GTCC)

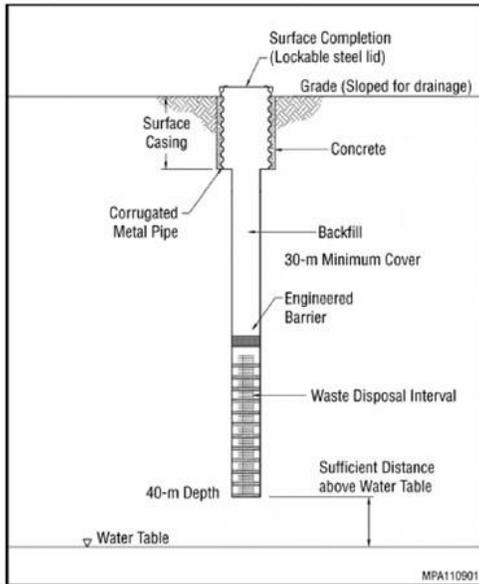
Borehole Options (cont'd)

- For purposes of our discussions boreholes come in three “sizes”
 - Shallow BH: 30 to 300 m depth (possible for GTCC and lower specific activity and lower “proliferation attractiveness” level materials)
 - Holes are above water table
 - Intermediate depth BH: 300 to 2000 m depth
 - Probably below water table and adaptable to higher specific activity wastes
 - Deep boreholes: 2000 to 5000 m depth (possible for higher activity and high proliferation “attractiveness level” materials)
 - Would be difficult to “re-mine”
 - Placement zone of BH well below water table

General comments on BH sizing and costs

- Higher diameters possible for shallow boreholes (1 to 12 ft or 0.3 to 3.7 meters)
- Intermediate and deep boreholes will likely need to be less than 0.5 m (20 inches) in diameter
- Drilling cost per unit depth (\$/m) increases with depth
 - Different unit drilling costs will be assumed for each of the three cases considered for DU
- Sandia estimates deep borehole costs at \$25 M to \$40M per BH.
- Deep borehole R&D program has been estimated at \$75M, including “pilot” borehole

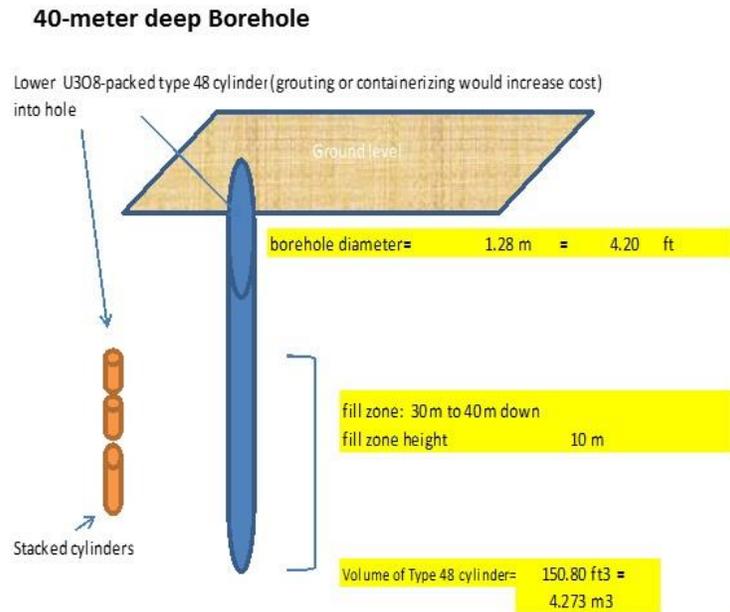
4a. Shallow Borehole



- Concept considered by DOE-EM for GTCC disposal (called “intermediate-sized” in DOE-EM EIS Report)
- Described in Module L-2 of 2012 Update to Advanced Fuel Cycle Cost Basis Report
- Capped to prevent re-drilling
- EM-proposal had normalized disposal cost of \$2750/m³ of disposal space (fill zone or waste disposal interval)

Diagram from 2012 Update to AFC-CBR

Assume DU308-Packed Type 48 Cylinders Could be Vertically Stacked End-to-End in Multiple Shallow Boreholes



- Hole diameter just over 48" would allow direct emplacement of DOE-legacy DU308-filled cylinders from B&W deconversion facilities at Paducah and Portsmouth
- For 10m high "fill zone" 3 cylinders could be stacked "end to end"
- At bulk density of 2.6 MT/m³ each cylinder holds 10 MT U3O8
- ~185,000 boreholes req'd to disposition U3O8 from 700,000MT DUF6
- 7.4 km² field for boreholes if centerlines are 20 m apart.

Shallow boreholes cont'd

- Unit disposal cost inversely proportional to packed bulk density of U3O8 powder in cylinder
- At 2750 \$/m³ of borehole “fill zone”, 90% occupancy of fill zone by cylinders, and bulk DU3O8 density of 2.6 MT/m³, unit costs of **1.18 \$/kg DU3O8 or 1.39 \$/kg DU are calculated**
- For lower bulk DU3O8 powder densities:

–	Density	\$/kgDU3O8	\$/kgDU
–	2.3	1.35	1.57
–	1.8	1.70	2.00
- Number of boreholes and land area increase inversely proportional to U3O8 bulk density
- Borehole drilling cost just below \$1000/m of borehole (top to bottom)
- Drilling technique probably large auger rather than conventional drill bit

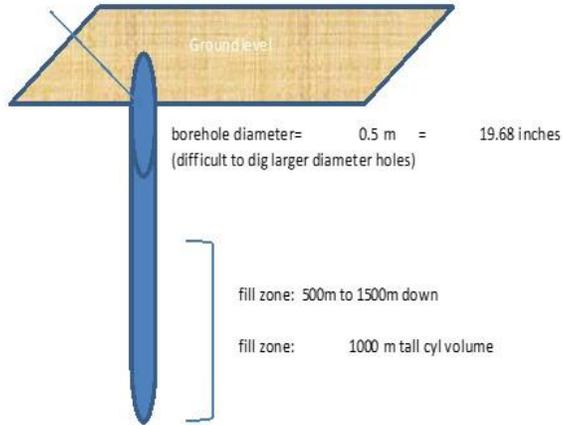


4b. Intermediate Depth Boreholes

Assume DU308-Powder could be poured directly down multiple Intermediate Depth Boreholes (or packaged in narrow steel cans for vertical in-hole stacking)

1500-meter deep Borehole

Pour U308 straight down hole! (grouting or containerizing would increase cost)



volume of fill zone=	196 m ³ /BH	right circular cylinder
mass of DU308 per BH=	511 MT	at above density
# of BH to disp	700000 MT DUF6	
	558144 MT DU308	= 1093 boreholes !!

- 0.5 m hole diameter would allow reasonable drilling cost and higher depth would allow direct emplacement of DOE-legacy DU308 powder from B&W deconversion facilities at Paducah and Portsmouth or newer commercial facilities.
- Fill zone is one kilometer tall
- At bulk density of 2.6 MT/m³ each 196m³ fill zone holds 500 MT DU308
- ~1100 boreholes req'd to disposition U308 from 700,000MT DUF6
- 0.4 km² field for boreholes if centerlines are 20 m apart.

Intermediate depth boreholes cont'd

- Unit disposal cost inversely proportional to packed bulk density of U3O8 powder in fill zone
- At 3000 \$/m drilling cost for 1500 m deep holes, a cost of \$4.5M/borehole results
- Each borehole has ~200m³ of useable space (fill zone). At a bulk DU3O8 density of **2.6 MT/m³** each hole can hold ~500 MT DU3O8. Distributing the \$4.5M cost of each borehole over this mass results in unit costs of **9 \$/kg DU3O8 or 10.6 \$/kg DU** are calculated
- About 1100 BHs req'd to disposition the DU3O8 deconverted from 700,000 MT DUF6. Land space of 0.4 km² required if BH centerline to centerline spacing is 20m
- For lower bulk DU3O8 powder densities more BH needed, hence higher cost:

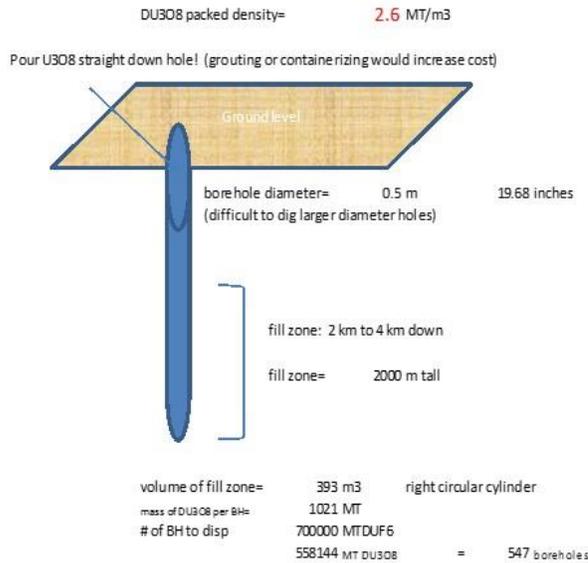
–	Density	\$/kgDU3O8	\$/kgDU
–	2.3	10.2	12.0
–	1.8	13.0	15.3
- Number of boreholes and land area also increase inversely proportional to U3O8 bulk density
- Intermediate unit depth (\$/m) drilling cost was selected as average of better known values for shallow and deep boreholes
- If U3O8 powder requires “canning” before emplacement, add about \$1/kgDU to above unit costs. (This might required to achieve higher packed density)

4c. Deep Boreholes

- Deep boreholes could provide non-retrievable disposal of powder or containers at depths of 3 to 5 km
- Deep boreholes should be thousands of meters below the water table
- Sandia gives cost of Nth-of-a-kind deep BH at ~\$25 million (17 inch dia and 5 km deep)
- Normalized cost is \$5000/m of depth (compared to \$1000/m for shallow depth BH)
- At this depth it might be possible to simply pour U3O8 powder down to form 2000m tall layer between 3 and 4 km depth
- Many BHs required to disposition U3O8 resulting from deconversion of 700000 MT DUF6 (depends on packing density in BH)
- Over 500 BHs required for density of 2.6MT/m³ bulk density

Deep Borehole Concept

4000 m deep borehole



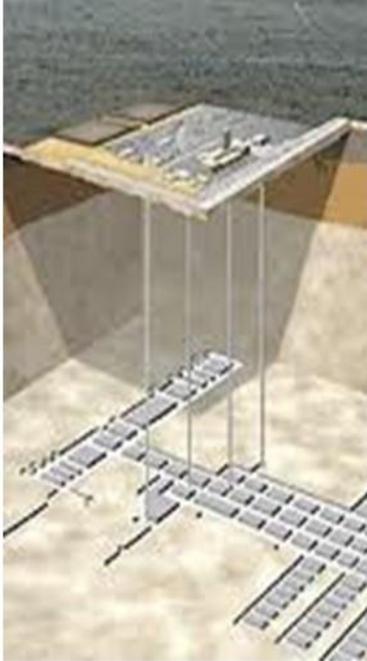
- 0.5 m hole diameter would allow reasonable drilling cost and higher depth would allow direct emplacement of DOE-legacy DU308 powder from B&W deconversion facilities at Paducah and Portsmouth or newer commercial facilities.
- Fill zone is 2 kilometers tall
- At bulk density of 2.6 MT/m³ each 393m³ fill zone holds ~1000 MT DU308
- ~547 boreholes req'd to disposition U308 from 700,000MT DUF6
- 0.22 km² field for boreholes if centerlines are 20 m apart.

Deep borehole disposal unit costs

- 4 km borehole costs \$20M
- ~547 required for 558144 MT DU308 at bulk density of 2.6 MT/m³. 0.22 km² land area req'd at 20m center to center spacing
- Program cost: \$11B !! For 700,000MT DUF6
- Cost per kg >>

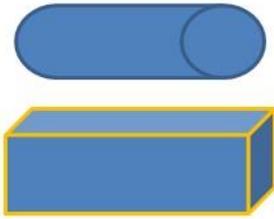
	DU308	DU
– Density of 2.6	19.6	23.1
– Density of 2.3	22.2	26.1
– Density of 1.8	28.3	33.4
- If “canning” of DU308 required before emplacement, add \$1/kgU to above

5. Emplacement in Deep-mined Salt Repository



- Waste Isolation Pilot Plant (WIPP) is America's only DGR
 - Located near Carlsbad NM
 - Licensed to accept carefully packaged transuranic (TRU) wastes from DOE sites
 - Most emplaced material is defense waste from Pu production (most in 55-gal drums)
 - Capital cost: \$3B (2012\$)
 - O&M cost \$200M/yr for 25 yr (2012\$)
 - Emplacement capacity: 175600 cubic meters per Land Withdrawal Act
 - Presently just over 50% full
 - Remaining space all reserved
 - Salt will slowly "flow" into mined galleries and engulf waste packages, hence waste considered non-retrievable
 - Similar concept has been studied for SNF and HLW
 - Concept now being studied for surplus weapons-grade Pu and HEU

Deep-mined Salt Repository, cont'd



3.85m³ U3O8
Volume in
Type 48
cylinder

5.44m³ of
WIPP-like
Gallery space
req'd for one
cylinder

If 558,144 MT DU3O8 dispositioned
At 2.6 MT/m³ powder density, ~55760
U3O8-filled cylinders would need emplace-
ment in WIPP-like facility. Space req'd
would be around 303,300 m³, nearly twice
The entire capacity of WIPP!

- Assume new WIPP-like DGR constructed for emplacement of U3O8-filled cylinders from 700,000 MTDUF6
 - Dividing WIPP Life cycle cost (\$8B) by its volumetric capacity gives \$45558/m³
 - DU3O8 occupies 70% of available space
 - At **bulk powder density of 2.6 MT/m³**, effective emplacement density is 1.84 MT/m³ (@10,010 kg U3O8 per cylinder)
 - Dividing unit capacity cost by emplacement density gives **~\$24,700/MT DU3O8**
- Salt beds in SW USA could easily accommodate new DGRs
 - Permitting would be major issue

Costs for Salt DGR disposal



- Life cycle cost of over \$14B to disposition DU3O8 arising from 700,000 MT DUF6
 - Life Cycle Cost and Unit Cost Higher if bulk DU3O8 density less than 2.6 MT/m³:

Density (MT/m ³)	\$/kg DU3O8	\$/kg DU
2.6	24.7	29.1
2.3	27.9	32.9
1.8	35.7	42.1

**Supporting Document 7 Presentation: Du and RU Disposal Costs
Fuel Fabrication Preface to FY 2021 Updates to the Supporting Documents**

Summary of Results

ID	Description	Cost [\$ /kg DU]
1	drums, cylinders, or SWBs disposed in shallow trench or vault	1.5 – 4.1
2	DUCRETE waste package overpack disposed in Yucca Mountain-like repository	4.5
3a	Drums or cylinders emplaced in YM-like repository, no additional excavation	12.2
3b	Drums or cylinders emplaced in YM-like repository, additional excavation required	39.8
3c	DU emplaced in HLW canisters inside co-disposal waste packages, emplaced in YM-like repository w/ add'l excavation	189
4a	DU powder or drums emplaced inside shallow (30-40 m) boreholes	1.2 – 3.0
4b	DU powder or drums emplaced inside intermediate-depth (500-1500 m) boreholes	10.6 – 16.3
4c	DU powder or drums emplaced inside deep (3000-4000 m) boreholes	23.1 – 34.4
5	Drums or cylinders emplaced in WIPP-like salt repository, additional excavation required	29.1 – 42.1

Disposal of Reprocessed U (RU)

- Not a lot of cost data in literature
- Countries who have RU are storing it
- Most complete existing cost analyses appear in *2009 Advanced Fuel Cycle Cost Basis Report*
- Numbers in AFC-CBD are re-examined here in light of new cost data for DU disposal above
 - RU can present challenges vis-à-vis DU, however nature of geologic medium may minimize these

Reprocessed U (RU) presents special issues

- U-232 formed during irradiation has very potent daughters, such as Thallium-208, with very penetrating gamma rays.
 - Activity increases rapidly in a few months and peaks at 70 yrs.
- Reprocessing does not completely remove all fission products (FPs) and transuranics (TRUS) from RU product stream
 - Ruthenium and technicium FPs often present in trace amounts
 - Neptunium and plutonium TRUs may also be present in trace amounts
- Amounts present depend on separation technology used for reprocessing
 - Aqueous separation results in purer RU product than pyro techniques
- Shallow low level waste disposal sites probably not acceptable for most radioactive RU forms, such as from pyroprocessing.
- RU Forms will be more akin to “Greater-than-Class C” waste or ILW

Current unit RU disposal cost values* in *Advanced Fuel Cycle Cost Basis Report (2012 Update)*

- Geologic Disposal of Aq Reprocessing-derived U3O8
 - Low 61 \$/kgRU If temp pkg could be emplaced
 - Most Likely 72 \$/kgRU If repackaging & transport required
 - High 93 \$/kgRU If regulatory & siting difficulties arise

- Geologic Disposal of Pyro Reprocessing-derived U metal
 - Low 75 \$/kgRU If contamination level just above aq RU
 - Most Likely 93 \$/kgRU If considerable addl handling req'd
 - High 150 \$/kgRU If regulatory & siting difficulties arise

* Conversion and packaging costs not included

DU options can be considered for RU and general comments made on likely unit disposal costs

- DUCRETE not likely option for RU
 - Worker radiation exposure during cask manufacture could pose difficulties
- Other DGR DU options could be very suitable for aqueous reprocessing derived U3O8
 - Workers and operations can already accommodate higher radiation environments associated with packaged SNF or HLW, hence RU poses smaller burden
 - One could add 20% to DU disposal costs. This is analogous to LWR fuel fab, where reprocessed U derived fuel carries an ~20% cost premium above “virgin” LEU derived fuel
 - DGR probably only feasible option for pyro-derived RU-metal
 - Need for special pre-emplacement packaging could add at least 5 \$/kgU to disposal cost

DU options for RU, cont'd

- Vault and shallow borehole options should be suitable for aqueous reprocessing-derived RU308
 - More robust packaging and higher radiation work environment might add a few \$/kgU to DU costs
- Intermediate and deep boreholes could accommodate pyro or aqueous-derived RU at some additional cost vis-à-vis DU
 - Direct disposal of powder not feasible
 - Special disposal cans would need to be designed and qualified for borehole emplacement
 - Remote emplacement machine would be needed in higher radiation environment
 - A SWAG for the additional cost vis-à-vis DU might be \$10/kgU for “aqueous” RU and \$20/kgU for “pyro” RU

RU: Comparison to 2009 AFC-CBD Unit Costs (K-2 and K-3 modules)

- New analysis shows that 2009 AFC-CBD costs for aqueously-derived RU disposition are on high side
- 2009 AFC-CBD costs for pyro-derived RU disposition are reasonable, especially in light of high uncertainty associated with pyro fuel cycle
- Disposition of RU products in DGRs already handling SNF or HLW products is the lowest cost option, since operations costs and overheads are distributed over all emplaced forms

\$/kg RU disposal cost summary

Option	Aqueous RU	Pyro RU
Packaged form in DGR (no excavation)	25	30
Packaged form in DGR (new excavation)	100	105
Shallow vault (similar to WCS)	4.5 to 6.5	n/a
Shallow borehole	3 to 5	
Intermediate depth borehole	21 to 25	30 to 25
Deep borehole	33-43	43-53

**Supporting Document 7 Presentation: Du and RU Disposal Costs
Fuel Fabrication Preface to FY 2021 Updates to the Supporting Documents**

New 1300 Mwe PWR LCC with Low Enrichment Plant Tail Disposition Costs							
Module	Description	Unit Cost Values		Flowrates Flow rate to support 1 reactor	One reactor COST		
		Unit cost value	Units		1 reactor annual cost (\$M/yr)	1 reactor \$/kgHM contrib	1 reactor cost of electricity contribution (\$/MWh)
A1	Uranium mining & milling	80	\$/kgU	216512 kgU/yr	\$17.32	703	1.69
A2	Thorium mining & milling	75	\$/kgTh	0 kgTh/yr	\$0.00	0	0.00
B	U3O8 to UF6 conversion	11	\$/kgU	216512 kgU/yr	\$2.38	97	0.23
C1	Uranium enrichment	105	\$/SWU	159055 SWU/yr	\$16.70	678	1.63
K1	Tails deconversion & disp	→ 10	\$/kgDU	191867 kg DU/yr	\$1.92	78	0.19
D	Fuel fabrication (U) Fuel fabrication (Th)	260	\$/kgU	24645 kgU/yr	\$6.41	260	0.62
E1 or E2	Pool or dry storage of spent fuel	100	\$/kgHM	24645	\$2.46	100	0.24
J	Low level waste C,P,&D						
	Total Fuel Cycle-related				\$47.19	\$1,915	4.60
R1	Thermal reactor (Non-fuel cycle related)	see above diagram		24645 kgHM/yr			
	Capital component				\$480.2		\$46.82
	O&M comp incl D&D				\$101.7		\$9.91
	Total reactor				\$581.8		\$56.73
	Reactor and fuel cycle total				\$629.0 \$M/yr		\$61.33 \$/MWh

One mill/kwh SNF disposal fee would add 416 \$/kgU or HM to above costs

**Supporting Document 7 Presentation: Du and RU Disposal Costs
Fuel Fabrication Preface to FY 2021 Updates to the Supporting Documents**

New 1300 Mwe PWR LCC with Very High Enrichment Plant Tails Disposal Cost								
Module	Description	Unit Cost Values		Flowrates	One reactor COST			
		Unit cost value	Units		Flow rate to support 1 reactor	1 reactor annual cost (\$M/yr)	1 reactor \$/kgHM contrib	1 reactor cost of electricity contribution (\$/MWh)
A1	Uranium mining & milling	80	\$/kgU	216512	kgU/yr	\$17.32	703	1.69
A2	Thorium mining & milling	30.8	\$/lb U3O8	0	kgTh/yr	\$0.00	0	0.00
B	U3O8 to UF6 conversion	75	\$/kgTh	216512	kgU/yr	\$2.38	97	0.23
C1	Uranium enrichment	11	\$/kgU	159055	SWU/yr	\$16.70	678	1.63
K1	Tails deconversion & disp	85	\$/kgDU	191867	kg DU/yr	\$16.31	662	1.59
D	Fuel fabrication (U) Fuel fabrication (Th)	260	\$/kgU	24645	kgU/yr	\$6.41	260	0.62
E1 or E2	Pool or dry storage of spent fuel	100	\$/kgHM	24645		\$2.46	100	0.24
J	Low level waste C,P,&D							
	Total Fuel Cycle-related					\$61.58	\$2,499	6.00
R1	Thermal reactor (Non-fuel cycle related) Capital component O&M comp incl D&D Total reactor	see above diagram		24645	kgHM/yr			
							Increases by 514 \$/kgU or HM	
						\$480.2	\$46.82	
						\$101.7	\$9.91	
						\$581.8	\$56.73	
	Reactor and fuel cycle total					\$643.4	\$M/yr	\$62.73 \$/MWh

One-mill per kwh SNF disposal adds \$416/kgHM to above fuel cycle total

Some General Comments

- Transportation costs not included in most of above analyses
 - Low radiation levels keeps them low compared to other costs. Commercial transport can be used
- Siting and permitting costs can be very significant
 - Difficult to estimate since extent of regulatory and legal difficulties hard to predict
- There is some future benefit in having retrievable option for DU forms
 - Emplacement location can be “rich” U-mine for fleets of future fast breeder reactors
 - Potential energy potential of DU from 700,000 MT DUF6 US legacy is equivalent to over half of US coal reserves
 - Assumes breeder reactor fleet requires only make-up uranium
- DUF6 stockpile will continue to grow with commercial US enrichment providers (URENCO in New Mexico, future Idaho plant, possible CENTRUS (formerly USEC) capacity