Advanced Fuel Cycle Cost Basis Report:

G Modules

Waste Conditioning, Storage, and Packaging

Nuclear Fuel Cycle and Supply Chain

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TABLES

ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
ALARA	as low as reasonably achievable
AVH	Ateliers Vitrification La Hague
AVM	Ateliers Vitrification Marcoule facility
BNFL	British Nuclear Fuels plc
BSG	borosilicate glass
CBFO	Carlsbad Field Office
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFTC	Consolidated Fuel Treatment Center
CsSr	cesium-strontium
CST	Crystalline Silicotitanate
D&D	decontamination and decommissioning .
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EAS	Engineering Alternative Studies
EM	Environmental Management
EPA	Environmental Protection Agency
F&ORs	Functional and Operational Requirements
FOEAS	Follow-on Engineering Alternative Studies
FP	fission product
GAO	General Accounting Office
GNEP	Global Nuclear Energy Partnership
GTCC	Greater-than-Class-C
HIPing	hot isostatic pressing
HLW	high-level waste
HTB	Bronze
HTO	Hydrous Titanium Oxide
ILW	intermediate level wastes
INL	Idaho National Laboratory
IWMS	Integrated Waste Management Strategy
IX	ion exchange
LCC	life cycle cost
LLW	low-level waste

MA	minor actinide
MLLW	mixed LLW
MTHM	metric ton of heavy metal
NETL	National Energy Technology Laboratory
NRC	Nuclear Regulatory Commission
NTWMP	National TRU Waste Management Plan
O&M	Operations and Maintenance
PEcoS	Pacific EcoSolutions Inc.,
PUREX	plutonium-uranium extraction
SA5	Sensitivity Analysis 5
SNF	spent nuclear fuel
TIG	Tungsten Inert Gas
TPC	total project cost
TRU	transuranic
TRUPACT-II	Transuranic Package Transporter Model-IIs
UREX	uranium extraction
USDOE	U.S. Department of Energy
WIPP	Waste Isolation Pilot Plant
WIT	What-It-Takes
WTP	Waste Treatment Plant

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Module G Series
Waste Conditioning, Storage, and Packaging

G-1. INTRODUCTION

This module includes all conditioning operations to prepare wastes for disposal or long-term storage in compliance with relevant Nuclear Regulatory Commission (NRC), U.S. Department of Energy (DOE), and Environmental Protection Agency (EPA) regulations. Wastes include high-level waste (HLW) according to 10 CFR 60.2 highly radioactive reprocessing wastes, spent nuclear fuel (SNF), low-level waste: Classes A, B, C, and Greater-than-Class-C (GTCC) waste (10 CFR 61.55), and transuranic (TRU) waste (40 CFR 191). Other than HLW conditioning, all other wastes are considered handled by disposal service contracts and do include dedicated facilities. Though not explicitly stated in each section, all waste operations will be handled considering ALARA principles and will maintain personnel dose and potential exposure of the public at or below regulatory limits. Also, where appropriate, all operations will maintain criticality control and incorporate intrinsically safe design with multiple layers of defense via engineering and administrative controls in that order of priority.

G-2. MODULE SERIES COST SUMMARY

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table G-1. The summary shows the reference cost basis (constant year U.S.$), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. The bolded items in the table are expressed in 2017$. (Refer to the "Production-based Costing" supplementary document following the "Modules" section of this report for additional details on the cost estimation approach used to construct the WIT tables.)

Costs for SNF, low-level waste (LLW), GTCC, and TRU handling are for services only and do not include dedicated disposal facilities, which are assumed to be separate commercial ventures or independently funded federal facilities similar to current LLW/mixed LLW (MLLW) landfills, and the Waste Isolation Pilot Plant (WIPP) repository.

[Note: All references for Module G are located in sections G5-10 (References) and G5-11 (Bibliography).]

Table G-1. WIT cost summary table for waste conditioning selected values (2009$ and escalated* to 2020$ and rounded consistent with technical cost estimate to the nearest tens or hundreds).

Reference Cost(s) Based on Reference Capacity	Upsides (Low Cost)	Downsides (High Cost)	Selected Values (Mode Cost)
G1–HLW			
HLW Borosilicate Glass	$2,200/kg FP	$6,600/kg FP	$5,000/kg FP
Escalated to Yr 2020$ **(G1-1A)**	**$2,600/kg FP**	**$7,900/kg FP**	**$6,000/kg FP**
Electrochemical HLW Treatment CFTC EAS	$12,015/kg FP	$18,122/kg FP	$15,100/kg FP
Escalated to Yr 2020$ **(G1-2E)**	**$14,300/kg FP**	**$21,600/kg FP**	**$18,000/kg FP**
U/Tc Separation and Solidification CFTC EAS	$161,836 /kg Tc	$231,496 /Kg Tc	$200,000/kg Tc
Escalated to Yr 2020 **(G1-2A)**	**$193,100 /kg Tc**	**$276,200 /Kg Tc**	**$238,600/kg Tc**
Cs/Sr Solidification and Packaging CFTC EAS	$30,700/kg Cs/Sr	$47,600/kg Cs/Sr	$40,000/kg Cs/Sr
Escalated to Yr 020$ **(G1-3A)**	**$36,600/kg Cs/Sr**	**$56,800/kg Cs/Sr**	**$47,700/kg Cs/Sr**
G2—SNF			
$80–100K/MTHM SNF	$50K/MTHM	$130K/MTHM	$100K/MTHM
Escalated to Yr 2020$ **(G2)**	**$60/kgHM**	**$160/kgHM**	**$130/kgHM**
G3—LLW			
CFTC EAS (debris)	$1,000/m³ LLW debris	$4,200/m³ LLW debris	$1,500/m³ LLW debris
Escalated to Yr 2020$ **(G3-1)**	**$1,100/m³ LLW debris**	**$4,600/m³ LLW debris**	**$1,600/m³ LLW debris**
$11,000/m³ LLW Liquid	$3,300/m³ LLW liquid	$22,000/m³ LLW liquid	$11,000/m³ LLW liquid
Escalated to Yr 2020$ **(G3-2)**	**$4,200/m³ LLW liquid**	**$27,700/m³ LLW liquid**	**$13,800/m³ LLW liquid**
$90,000/m³ Resins	$81,000/m³ resins	$99,000/m³ resins	$90,000/m³ resins
Escalated to Yr 2020$ **(G3-3)**	**$101,900/m³ resins**	**$124,600/m³ resins**	**$113,300/m³ resins**
G4—GTCC			
G4-1A Aqueous LLW-GTCC Offgas Absorber (H3, Kr, Xe)	$8,000/m³ gas	$15,000/m³ gas	$11,200/m³ gas
Escalated to Yr 2020$ **(G4-1A)**	**$9,500/m³ gas**	**$17,900/m³ gas**	**$13,400/m³ gas**
G4-1E EChem LLW-GTCC Offgas Absorber (H3, Kr, Xe)	$8,000/m³ gas	$15,000/m³ gas	$11,200/m³ gas
Escalated to Yr 2020$ **(G4-1e)**	**$9,500/m³ gas**	**$17,900/m³ gas**	**$13,400/m³ gas**
G5—GTCC Secondary			
INL Cost of Processing Defense TRU Waste and CFTC EAS	$19,000/m³ GTCC	$37,000/m³ GTCC	$27,000/m³ GTCC
Escalated to Yr 2020$ **(G5)**	**$22,700/m³ GTCC**	**$44,100/m³ GTCC**	**$32,200/m³ GTCC**

CH = contact-handled
CFTC = Consolidated Fuel Treatment Center
EAS = Engineering Alternative Studies
FP = fission product
GTCC = Greater-than-Class-C
HLW = high-level waste

LLW = low-level waste
MTHM = metric ton heavy metal
SNF = spent nuclear fuel
TRU = transuranic

*Escalation to 2020$ is from the year the particular G-module technology and cost basis was originally described and estimated: escalation is 26% from 2006, 19% from 2009, and 8% from 2015. See the Main Chapter of the AFC-CBR for more details on cost escalation.

Module G1

High-Level Waste (HLW) Conditioning, Storage, and Packaging

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G1 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004	All	Version of AFC-CBR in which Module first appeared: 2004
	2017	All	Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges: 2009. 2009 data was escalated to 2017$ for this latest revision.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module G1
HLW Conditioning, Storage, and Packaging

G1-MD.   SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**

- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only.

- **Estimating Methodology for latest (2009 AFC-CBR) technical update from which this FY21 update was escalated:** Bottom-up estimates for waste handling facilities and operations for UREX-1a aqueous and Electrochemical reprocessing plants assessed as part of the Engineering Alternative Studies (EAS) during the GNEP. Unit costs were calculated for various types of fission product conditioning, storage, and packaging. (Geologic disposal is not included).

G1-1.   BASIC INFORMATION

Module G1 receives high-level waste (HLW) from a reprocessing facility, stabilizes the waste, provides interim storage of the treated waste, and packages the waste in preparation for transport to a disposal site. According to the Nuclear Waste Policy Act, HLW includes:

"The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing, and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and…

Other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation (DOE 2005)."

Several examples of existing and planned HLW facilities exist, including two examples in the U.S., the Defense Waste Processing Facility (DWPF) and the West Valley Demonstration Project. These facilities represent completed HLW conditioning facilities. The Waste Treatment Plant (WTP) at Hanford is under construction with a current forecast operational date of 2022 for some less complex wastes and 2039 for more difficult wastes. All these facilities are designed to vitrify the wastes into a glassy form in compliance with 40 CFR 268, "Land Disposal Restrictions, Subpart D Treatment Standards."

Though other stabilization techniques and waste forms could be cost-effective for HLW, the current baseline in the U.S. is defined by DOE in the Waste Acceptance System Requirements Document (DOE 2008) and the DOE-Office of Environmental Management Waste Acceptance Product Specification for Vitrified High Level Waste Forms (DOE 2012) as borosilicate glass. This baseline is similar to operations in France and Japan, but other types of glass and crystalline waste forms are being considered as part of the evaluation of used fuel processing for fissile material recycle. The electrochemical processing fuel recycling flowsheet under development by INL includes production of metallic and glass-bonded ceramic waste forms. A ceramic waste form is planned for disposal of plutonium though these waste forms have not yet been adopted in the baseline.

In the uranium extraction (UREX)+ aqueous reprocessing system envisioned, light-water reactor oxide fuel is dissolved in nitric acid and low-enriched uranium is recovered for reuse or disposal as low-level waste (LLW) if sufficiently decontaminated (See Module K2). Transuranic (TRU) elements would be recovered in one or two partitions and either recycled in metal fuel to be consumed in a fast spectrum reactor or disposed of in a geologic repository. Zirconium fuel cladding hulls and other hardware components are decontaminated and packaged for disposal. Gaseous fission products are captured separately and packaged for disposal. Cesium and strontium may be segregated for interim "decay-storage" for ~300 years and not sent to a geologic repository. Presuming the chemical separation efficiency goals are met, after decay of the cesium and strontium to near-surface LLW disposal standards, these wastes would be disposed accordingly as Greater-than-Class-C (GTCC) not HLW. This assumes the stream does not contain significant amounts of long-lived fission products or TRU, and a long-term (>300 years) storage facility is licensed to store the cesium and strontium pending decay. Technetium is captured and treated separately to enhance the waste form and allow increased repository loading of this HLW. The remaining fission products are HLW and stabilized in a waste form for the repository. Different conceptual designs for treatment of the HLW streams incorporate calcination, steam reforming, precipitation with filtration and drying, or the baseline glass melters. Regardless of which design is used for estimating purposes, it is important that the costs used for reprocessing and the costs used for preparing HLW for disposal in a geologic repository do not double-count the waste treatment costs.

In the electrochemical processing system, metal fuel from fast reactors is dissolved electrolytically in an electrorefiner, with the chopped fuel submerged in a molten lithium/potassium chloride salt bath. Uranium and TRU are to be captured for recycle at a cathode, while zirconium from the fuel matrix and noble metal fission products including technetium remain with the stainless steel fuel hulls at the anode. The cladding/Tc/Zr/fission product (FP) stream is to be melted into ingots for disposal as a metal HLW form in a geologic repository. Waste salts containing the balance of FP including the cesium, strontium and iodine are to be absorbed into zeolites and bonded using borosilicate glass to make a ceramic HLW form for disposal in a geologic repository.

All the streams from reprocessing could be considered HLW under current regulations. If the developed separations are assumed to be adequate to meet disposal and recycling specifications and that the decay storage strategy is licensed and a repository for commercial TRU wastes is created, the steams from fuel processing may have more cost-effective disposition pathways available. A summary of the potential streams from aqueous UREX and high-temperature electrochemical processing and their planned and possible alternate disposition pathways is shown in Table G1-1. Some entries in the table are undefined because testing has not yet been done, or data are unavailable.

Whether the HLW ends up in baseline glass or in a different form will be dictated by the reprocessing design and government policy. For the purposes of this document, cost bases for the treatment of aqueous waste are vitrification facilities similar to defense HLW vitrification facilities (DWPF and WTP), since this technology is expected to remain the baseline for at least the next 20–30 years. Shipping and disposal costs are all based on canisters of glass. The costs reported here are based on the DWPF actual costs and Consolidated Fuel Treatment Center (CFTC) Engineering Alternative Studies (EAS) estimates. None of these estimates include the cost for transportation or disposal of glass canisters. However, potentially higher waste loading and waste forms with greater density are considered in assigning the range of values in the cost tables.

Electrochemical waste processing costs reported here are those developed as a part of the CFTC Follow-on EAS (FOEAS). The study includes cost associated with the zeolite/borosilicate glass-bonded process to make a ceramic HLW form and the production of a lanthanide glass for disposal in a geologic repository.

Table G1-1. Fuel reprocessing streams.

Aqueous UREX processing of LWR fuel	Planned Disposition			Example Alternative Disposition		
	Disposition	Potential Waste Form	Range of Waste Loading	Disposition	Potential Waste Form	Range of Waste Loading
U	LLW	Oxide powder or grout	30–100%			
				TRU waste	Oxide powder or grout	30–100%
				HLW	Glass or glass-like, Synroc, or iron-phosphate	20–40%
				Recycle via re-enrichment	Fuel raw material	Not waste
				Recycle as DU metal	Metal	Not waste
TRU	Fuel	Metal FR fuel	Not Waste			
				Burn in LWR	MOX or inert matrix fuel	Not waste
				TRU waste	Oxide powder or grout	30–100%
Cs/Sr	HLW	Ceramic formed from bentonite clay	10%			
				HLW	Glass or glass-like, Synroc or iron-phosphate	10–20%
				GTCC	Ceramic or grout	10–20%
Tc	HLW	Metal	0–5%			
				HLW	Codisposed with other FP in glass	<1%
				HLW	Low-temp ceramic	10–30%
				GTCC	Low-temp ceramic	10–30%
I	HLW	Ag-zeolite in grout	5–10%			
				HLW	Anionic	5–10%
Balance of FP	HLW	Glass	20–50%			
				HLW	Synroc, iron-phosphate	30–70%
				HLW	Crystalline, low-temp	10–30%
				GTCC	Grout	20–50%
Zr Cladding Hulls	GTCC	Compacted Metal	100%			
				Re-use in FR metal fuel alloy	No waste	No waste
				HLW	Compacted metal	100%

Table G1-1. (continued).

Aqueous UREX processing of LWR fuel	Planned Disposition			Example Alternative Disposition		
	Disposition	Potential Waste Form	Range of Waste Loading	Disposition	Potential Waste Form	Range of Waste Loading
Electrochemical						
U/TRU	Reuse in burner FR	Not waste	Not waste			
				U only as LLW near surface disposal	Metal or macroencapsulated	60–100%
				TRU waste	Metal or macroencapsulated	60–100%
				HLW	Glass or glass-like, Synroc, or iron-phosphate	20–40%
SS Cladding, Zr, Tc, noble FP	HLW	Metal waste form with Tc and matrix Zr	100%			
				TRU waste	Compacted metal	100%
				HLW	Compacted metal	100%
Cs/Sr/I Excess Salts and other FP except lanthanides	HLW	Glass-bonded salt in zeolite	10%			
				HLW	Glass or glass-like, Synroc, or iron-phosphate	10–20%
				GTCC	Grout	10–20%
Lanthanides	HLW	Lanthanide glass	50%			
				HLW	Glass or glass-like, Synroc, iron-phosphate	20–40%
FP=Fission Product MOX=Mixed Oxide FR= Fast Reactor SS=Stainless Steel						

G1-2.   FUNCTIONAL AND OPERATIONAL DESCRIPTION

All HLW will be handled remotely, in specially equipped hot cells, typically designed with 2 to 4-feet-thick concrete walls, oil-filled windows, and manipulators. Waste will be received from tank farm or solid storage operations and held in interim storage that can be mixed sufficiently to allow representative

sampling. Samples will be acquired remotely and analyzed to characterize wastes, including a full suite of α, β, and γ emitting radionuclides, toxic metals, and organic constituents likely to be present based on the selected process. In addition to establishing the basic chemistry of the waste to develop a recipe for a waste form, the analytical data will be reviewed as required to determine if the waste is hazardous according to the Resource Conservation and Recovery Act and if the waste contains any listed organic constituents. Once characterized, laboratory support facilities will develop a reliable chemical recipe for converting the waste to a borosilicate glass meeting disposal requirements.

The main process area of the facility will be equipped with reliable melter technology to convert the waste with additives into the desired glassy waste form, or parallel technology to produce a nonglass acceptable waste form. This area will be remotely operated as well, and all maintenance will be conducted remotely or constrained by very limited access preceded by decontamination. Equipment will be designed for reliable operation and remote disassembly where possible. The facility must have the capability to conduct routine maintenance as well as nonroutine activities, such as change out of damaged or worn out large equipment including the melter itself.

Facilities will also be equipped with postprocess remote sampling and analytical capabilities to characterize waste form products including durability in standard tests such as the Product Consistency Test (ASTM 2008) and the Toxic Characteristic Leach Procedure (EPA 1992) if deemed necessary. The facility will be equipped with an offgas treatment system designed such that when operated in coordination with the melter system retention of materials in the waste form is maximized and gaseous effluents meet Maximum Achievable Control Standards, as designated in the facility permit. This will probably require recycle of filter catch materials to the main process equipment (melter), include specialized operation such as specific RedOx chemistry control in the melter, and require operation with a cold-cap (layer of liquid feed covering most of the molten glass surface). The offgas system for a thermal process for highly radioactive materials may make up 60% or more of process space, and the hot-cell area will likely drive facility capital cost.

The facility will likely recycle water with the evaporator bottoms being recycled to maximize waste incorporation in the glass and the condensates collected for nitric acid recovery, and additional decontamination. The purified water will then be recycled and any excess water will likely be stabilized in concrete or a similar stabilizer and disposed of as LLW. The cost of acid recovery and effluent treatment is not included in this module.

Offgas filters, clothing, tools, and miscellaneous hardware will also generally be disposed of as LLW. There is a potential for generating GTCC and TRU wastes, but a properly designed waste management and decontamination system should minimize this occurrence.

This module generally does not include additional separations that could produce several streams from the HLW. Fractionation of the reprocessing wastes is contained within Modules F1 and F2/D2 dedicated to reprocessing.

In the following sections, the Functional and Operational Requirements (F&ORs) for HLW (with potential to reclassify to either LLW or GTCC) are examined in terms of waste conditioning and waste forms, canister sizes, and storage.

G1-2.1 Waste Forms, Canister Sizes, and Storage of Heat Generating Wastes

Solidification of the waste serves the two main purposes of immobilization of waste for storage, transport, and emplacement in a permanent disposal facility. Interim storage is normally required to allow further decay of the major heat emitting nuclides, and therefore reduce the early thermal loading of the

disposal facility. Thermal, mechanical, and chemical stability of the waste form is required including effects of irradiation and leaching.

Various waste forms and corresponding waste immobilization processes are known for HLW. Calcines are products or intermediates obtained by partial or complete removal of volatile components of the waste, such as water and nitrates, at temperatures of 400–900°C. This creates a mixture of oxides in particulate form and with a specific surface of 0.1–5 m^2/g. Calcine powders may not be very stable because of the chemical properties of some constituents, large surface area, low thermal conductivity, and friable nature of the solids creating fine dust. Depending on calcination temperature, calcines may have residual water and nitrate content. Calcine powder may be pressed or solidified within cements or concentrated solutions grouted. If waste temperatures, radiation, or canister corrosion effects are sufficient to release water, NOx or hydrogen, then canister venting, inspection, and offgas treatment may be needed (Streatfield et al. 2006).

For passive long-term decay storage, higher process temperature, refractory, near-inert waste forms, such as glasses and ceramics are preferred. For heat generating wastes, waste form dimensions may need optimization to limit center line temperatures to acceptable values. The more important immobilization alternatives are calcine, ceramics, glass, glass ceramics, and cement (Benedict et al. 1981) (see Table G1-2).

Table G1-2. Immobilization waste form options.

Alternative	Calcine	Glass	Ceramic
Basic	Fluidized bed (particulates) Pot (cake)	Borosilicate (cylinder) Phosphate (cylinder)	Aluminosilicate Bentonite
Advanced	Supercalcine (additives, high T)	Borosilicate glass ceramic (cylinder)	Synroc (multi-phase ceramic) – Hi T, HIP
Composite	Multibarrier (e.g., pyroC, SiC in metal matrix)	Vitromet (glass/glass ceramic in metal matrix)	Glass ceramic (e.g., puck crystallized glasses and sodalite in glass matrix)
Cement-vented Canister	Low T encapsulation of concentrated solution or calcined particles		Higher temperature specialized cements (e.g., supercalcines)

There is generally an increased processing cost for refractory, inert waste forms. This may take place through need for high-temperature operation, corrosive conditions limiting equipment lifetimes, volatilization of selected fission products requiring complex off-gas systems and waste recycle. Synrocs often require small batch operations using hot isostatic pressing (HIPing) at high temperature and with relatively long process cycles.

Waste forms may incorporate differing waste concentrations to meet waste performance and economic goals. Waste packaging and transportation costs are significant so that reduction of package number is desirable. However, thermal limitations apply to transportation, disposal and the waste form itself, and excessive fission product (FP) concentrations reduce the chemical performance of waste and may cause excessive internal temperatures. Composition limitations are typical for glasses where either phase separation or lack of glass forming occurs. For borosilicate glasses, for example, the FP oxide limit is normally considered to be around 20–25% by weight (plus process additives) using existing hot-wall melters. Higher concentration may create a distinct yellow crystalline phase formed of alkaline and alkaline earth molybdates. This readily soluble phase contains Cs-137 and Sr-90. Glasses can be formulated to incorporate most fission product and actinide oxides with good stability. Devitrification occurs above the glass transition temperature, for example at elevated temperatures of ~500°C for phosphate and ~600°C for present borosilicate glasses. Some processes employ controlled crystallization

to glass ceramics to create known waste form properties. Other waste form composition/temperature limitations may arise from a wide variety of limits such as melting, volatization, and recrystallization into new phases, chemical reaction, canister pressurization, etc. Composition is not a direct limitation for calcines, which are amorphous, but high-heat load may cause further chemical decomposition, canister corrosion, and pressurization. Grouts are normally used to immobilize mineral ion exchange (IX) materials used for treatment of LLW and (in Europe) for intermediate level wastes (ILW) liquid wastes, but have also been used for encapsulation of low specific decay power raffinates from specialized recycling operations.

Industrial practice for HLW vitrification tends to use large canisters for low specific decay heat defense wastes (e.g., 0.61 m o.d., 3 m height and 2.1 t filled mass) for Savannah River DWPF, and small canisters for high-specific decay power LWR wastes (e.g., 0.43 m o.d., 1.3 m height and 0.5 t filled mass) for Ateliers Vitrification La Hague (AVH) (IAEA 1992). Even smaller diameter canisters, o.d. 0.3 m, have also been used at PAMELA (Germany) and WIP (India). In general terms, canisters with diameters less than 0.2–0.15 m diameter are not favored industrially due to difficulties of filling with molten glass due to bridging, potentially more thimble tubes due to retention of moderate l/d ratios for canister cooling, increased pressure drops with high-air velocities, and possible limited cost reduction of storage with decreasing thimble tube diameter. KfK Germany developed a process where HLW phosphate glass beads were cast and then embedded in molten metal in a canister. Such an approach or other internal features for heat conduction may be especially useful for CsSr vitrification of short-cooled, high-loaded fission products.

For LWR fuel of typical burn-up of 40 GW(t).d/t(iHM), the decay powers are given in the Table G1-3, (Bergelson et al. 2005).

Table G1-3. Decay heat power of FPs and transuranics (Pu, Am, Cm) during long-term storage, W/t(iHM).

t (y)	Beta	Gamma	Total FP	Actinides + FP
0	2300	615	2910	3180
1	1470	530	2000	2260
3	892	451	1340	1600
10	617	351	968	1230
30	376	206	582	845
100	71.0	39.5	111	330
300	0.648	0.396	1.04	149
1000	0.0136	0.00752	0.0211	63.8
3000	0.0135	0.00742	0.0209	24.9
10,000	0.0131	0.00707	0.0202	14.7
30,000	0.0122	0.00615	0.0183	5.60
100,000	0.00936	0.00380	0.0132	0.859
300,000	0.00478	0.00097	0.00573	0.239

Data in Table G1-3 shows both total FP and total FP with transuranic (Pu, Am, Cm) contributions to decay power. Often the Pu contribution is omitted as vitrified HLW includes minor actinides, but not Pu. The total FP decay power reduces by 40% in the period 10-year cooled to 30-year cooled, which indicates the major contributions of Cs-137 ($t_{1/2}$ = 30y) and Sr-90 ($t_{1/2}$ = 28y) to decay power in this period.

Heat generation in immobilized HLW and CsSr waste causes the waste form to be at elevated temperatures for more than 100 years. With some simplifications, the maximum temperature difference between the centerline and surface of a long cylindrical waste form is given by:

$$\Delta T_{max} = q\, r^2 / 4\, \kappa$$

Where

q = power density, W/m^3

r = radius of the cylinder

κ = waste form thermal conductivity, W/(m.°C).

The surface temperature is given by the storage conditions including canister wall and waste surface/canister interfacial properties. This enables scaling of canister radius against heat loadings from existing commercial practice (IAEA 1992). Representative values for conductivity of waste forms are given in Table G1-4 (Benedict et al. 1981).

Table G1-4. Thermal conductivity ranges for various HLW forms in temperature range 100–500°C.

Waste Form	Thermal Conductivity, κ W/(m.°C)
Particulate calcine	0.2–0.3
Phosphate glass	0.8–1.2
Borosilicate glass	0.9–1.3
Borosilicate glass ceramic	1.5–2.0
Particulate calcine or glass beads in metal matrix (e.g., vitromet)	~10

Waste form conductivity clearly has a major influence on centerline (peak) temperature and corresponding canister dimension (radius), see Figure G1-1, (Benedict et al. 1981).
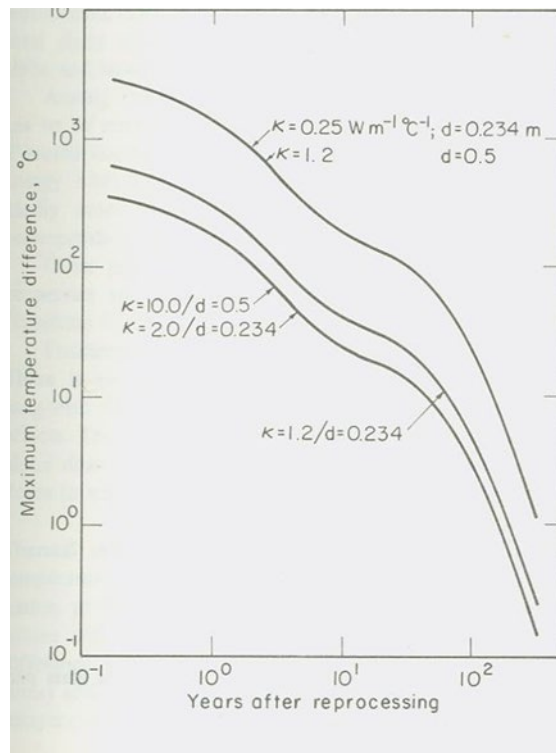
Figure G1-1. Maximum centerline temperature difference of waste form as a function of decay time.

Figure G1-1. Calculated maximum temperature difference in a cylinder of solidified waste for different diameters and thermal conductivities as a function of time (years) after recycling.

The heat generation rate is based on fission products and minor actinides incorporated into a waste form specific volume of 70 L/t(iHM). The originating SNF burnup is 30 GW(t).d/t(iHM) and recycling taking place at 150 days SNF decay.

At the assumed waste loading, Figure G1-1 indicates maximum temperature differences for glass ceramic waste with canister diameter of about 0.5 m of between the waste center line and surface of >1,000°C ($\equiv$ 100 W/L) and >100°C ($\equiv$ 10 W/L) for 1 year and 10 years decay after recycling respectively.

In the present study, borosilicate glass is considered the reference HLW form. This is conservative since it is somewhat more thermally restrictive than some synrocs and other ceramics. For civil design, it is generally preferable to restrict natural convection cooling air discharge temperatures to around 150–200°C as concrete structural components are damaged by long-term contact with air at temperatures approaching 100°C. However, higher values can be engineered. Air cooling in forced convection stores would be less limiting, but for a long-term decay store, there is likely to be conservatism concerning highly rated systems and effects of cooling failure. This suggests that a maximum temperature difference, ΔT, between waste centerline and surface of around 300°C may be appropriate assuming a centerline maximum design temperature of ~500°C. For a canister with diameter 0.5 m containing borosilicate glass HLW, a maximum specific thermal power in the range 10–30 W/L appears suitable. Raising the glass transition temperature by ~200°C increases the maximum thermal power by about 60%.

G1-2.2   Potential Waste Forms for Immobilization of Cesium and Strontium

The most troublesome Cs and Sr isotopes are Cs-137 ($t_{1/2}$=30.07 y: 0.66 MeV γ and 0.514 MeVmax β-) and Sr-90 ($t_{1/2}$=28.78 y: 0.546 MeVmax β-), so their activities remain a concern for ~300 years (i.e., ~10 half-lives). These two isotopes generate a major portion of the decay heat in spent nuclear fuel over the first 100 years of storage, but then are essentially stable. Removing Cs and Sr for decay storage will reduce the short-term heat load on a repository waste form.

Fission product oxide mass, excluding noble gases, is ~1 kg(FPOx)/GW(t).d, and so for a metric ton, t, of SNF at 40 GW(t).d/t(iHM), the mass of FP oxides is about 40 kg. Cs and Sr form about 10 atom % of the FPs, of which around half are the major heat emitting isotopes (Cs-137 and Sr-90). Total CsSr also form around 10% by weight of the FP oxides, that is 4 kg/t(iHM) of spent fuel. Total CsSr-Rb-Ba form around 15% by weight of the FP oxides, that is 6 kg/t(iHM) of spent fuel. From Table E4-2, where Cs-137 and Sr-90 are the only major FP isotopes with half lives between 10–50 years, the decay power of CsSr is seen as about 1 kWt(iHM) at 10 years ex-reactor. Alternatively the CsSr decay power can be expressed as ~¼ kW/kg(CsSr) at 10-years cooling. In engineering terms, the specific decay power of CsSrOx is about 10 times that of overall FPOx at 3–20 years cooling.

Recently, interest in separation of Cs and/or Sr during remediation of long-stored HLWs and for advanced fuel cycles has stimulated developments in waste forms tailored to CsSr immobilization. These include variants of waste forms for HLW and several new matrices (see Table G1-5), which is representative rather than complete. The various minerals formed have differing capacities for Cs and Sr.

These potential CsSr waste storage forms evolved from upstream processing needs. Bentonite (including commercial UOP IE-911), and hydrous titanium oxide (HTO) are examples of IX materials used to selectively adsorb Cs, Sr, etc., from stored, complex chemistry salt HLWs to provide partitioning of waste for optimized waste management. These IX materials bearing low-medium Cs, Sr concentrations are heat treated by sintering, generally in the temperature range 500–1,000°C. This causes removal of water, recrystallization, denitration, and additional phases, and ultimately removal of hydroxyl groups. By contrast, the advanced fuel cycle processes (e.g., UREX+ [Vandegrift et al. 2004]) create salt-free product streams of CsSr (e.g., nitrate and carboxylic acid based). These are not constrained by feed of mineral IX materials and can be used to form the complete range of waste forms from pure CsSr oxides/chlorides to

glasses to freely tailored ceramics. The uses of zeolites (i.e., micro-porous crystalline solids with well-defined structures) generally contain silicon, aluminum, and oxygen in their framework and cations, and/or other molecules within their pores. For CsSr recovery in molten salt, electrochemical waste forms are more likely to be aluminosilicate ceramics or aluminosilicate glass ceramics.

Table G1-5. Representative CsSr-Rb-Ba waste forms.

Matrix	CsSr Composition	Composition Matrix, (% wt)	Process	Reference
Cement	4% Zeolite A, 5mEq/g	Pulverized Fuel Ash, Ordinary Portland Cement	Grouting ambient T Maintain ≤95°C	El-Kamash et al. 2006
Alumino-silicate (Steam reform)	27%Cs / 8%Sr $SrCO_3$ $CsAlSi_2O_4$	Pollucite/hydroceramic Slawsonite	Steam reform CsSr-Ba with carbon & alumino-silicate clay at ~700°C	Ortega and McDeavitt, 2007 Law et al. 2007
Bentonite (alumino-silicate) Dry Sinter	≤40% Cs loading	Celsian Pollucite Hydroxyl-apophyllite	Dry sintering bentonite clay containing Cs, Sr, Rb, Ba to 600–1,000°C	Kaminski and Merz, ANL.
Crystalline Silicotitanate (CST) and Niobate IX	Cs_2O ~ 20% wt	$Cs_2TiSi_6O_{15}$ $Cs_3TiSi_3O_{9.5}$ and Ti analogue of Pollucite $CsTiSi_2O_6$	Calcining CsSr soaked UOP CST IE-911 in air at 900–1,000°C	Elder et al. 2000 Luca et al. 2006a,b
Borosilicate Glass High mp glass	Cs_2O 13% wt and SrO 7% wt PNNL ~40%wt	Na_2O 10-20 B_2O_3 10-17 SiO_2 45-50 Al_2O_3 2-5 Ba,Pb,TiOx 4-6	Calcination and Melting High-melting glass	Aloy et al. 2007
Hexagonal Tungsten Oxide Bronze (HTB)	Cs_2O ~12% wt or SrO ~5% wt	$Cs_{0.13}Mo_{0.03}W_{0.97}O_3$ $Sr_{0.05}Mo_{0.03}W_{0.97}O_3$	CsSr adsorbed HTB, Calcine 500–1,000°C in air.	Luca et al. 2006a,b
Synroc-C Hydrous Titanium Oxide (HTO)	CsSr-Rb-Ba 12 %wt	Hollandite Rutile Titanates	Calcination 750°C & HIP 1,275°C, 30MPa, 1h	Carter et al. 2007
Cs/Sr Oxides	Cs_2O/SrO	Pure	Calcination	-
CsCl	100% Cs salt in capsule in pool	CsCl, 35kCi 190W	IX separation and Evap	National Research Council, 2003
SrF_2	Sr salt in capsule in pool	CsF_2, 33kCi 260W	IX separation and Evap	National Research Council, 2003

High-level waste vitrification is well known as a complex technology with significant cost impact on existing plutonium-uranium extraction (PUREX) commercial and defense recycling waste management. Advanced fuel processes generally partition FP and actinide species into more streams (e.g., seven for UREX+4). Some of these, (CsSr), have medium radioactive lifetimes and means have been sought to optimize the waste immobilization process to the waste lifetime, including storage requirements. For substantial masses, CsSr wastes need cooling for periods of 100–200 years. AFCI has examined use of a steam reforming process to fabricate alumino-silicate waste forms for CsSr storage (Law et al. 2006).

The UREX+ suite of processes has a separation segment, CCD-PEG in UREX+1a (Law et al. 2004) or FPEX in UREX+1b (Law et al. 2007), for recovery of CsSr-Rb-Ba from the raffinate of the UREX segment. Both of these technologies provide simultaneous solvent extraction of Cs and Sr together with the majority of Rb and Ba. With CCD-PEG, the CsSr by-product is stripped using an organic amine and carboxylic acid mixture while FPEX uses dilute nitric acid as strip. Steam reforming has been developed for stabilization of streams because it can produce a solid waste form while retaining the Cs and Sr in the solid, destroy the nitrates and organics present in these aqueous solutions, and convert the Cs and Sr into leach resistant aluminosilicate minerals. The waste form is intended to meet a 300 year, 10 half-life period of storage prior to projected LLW disposal complying with Class C waste criteria.

A bench-scale steam reforming pilot plant has been operated at Idaho National Laboratory (INL) with several potential CsSr feed compositions and steam reformed product has been generated and analyzed (Law et al. 2006). A small, but representative fluidized-bed was used to conduct steam-reforming tests to produce mineralized granular product. Operating conditions of 700°C, ~3% H_2, ~4% CO, 70% CO_2, and 20% steam were used to decompose nitrates and organics. A starting bed of 100–300 micron aluminum oxide particles was used and Sagger clay slurried with the feed to produce pollucite and other alumino-silicate minerals. Excess clay was used to mineralize the cationic feed constituents. The clay particles are less than 10 μm to achieve a high-surface area for reaction. The final bed material in each run was generally a granular material much like the initial aluminum oxide starting bed with some additional smaller diameter solids. The bench-scale steam reformer tests successfully converted cesium/strontium strip products to a solid form without volatilizing the Cs. Results also indicate that with optimization of the steam reforming operating parameters, 100% mineralization is possible (Law et al. 2006). The bed waste product material may be compacted, for example, within canisters to form pucks, which may be loaded into an over-pack.

A collection of EAS related to a commercial scale UREX+ separations plant were commissioned by DOE and carried out by a multi-national laboratory team in 2006–2008. EAS investigated features of a canyon approach for a commercial plant, with expected throughput of ~3,000 t(HM)/year, with three solvent extraction lines. The FOEAS evaluation assumed a smaller plant throughput (~800 t(HM)/year UREX+) with re-examination of facility layout options, requirements, alternate flowsheets, etc. (WSRC 2007, 2008).

In the EAS, an engineering proposal and costing of the proposed storage of the UREX+ cesium-strontium (CsSr) waste stream was presented. The study was based on the UREX+1a process, throughput of 3,000 t(iHM)/year mixed LWR fuel of 60 GW(t).d/t, and formed a variety of products and wastes, including an aluminosilicate mineral powder CsSr waste intended for a 300-year period of storage prior to projected LLW disposal. This study demonstrated reasonable feasibility but was not an economic optimization and further studies were performed.

The FOEAS was based on the UREX+1b process throughput of 800 t(iHM)/year mixed LWR fuel of 60 GW(t).d/t and formed a variety of products and wastes. For CsSr, three waste forms were examined conceptually: a sintered bentonite and two vitrified CsSr options with differing CsSr loadings. As for EAS, these would need nominal 300-years storage for compliance with Class C waste disposal. Other geological disposal scenarios may be feasible, but are not well defined yet and so are not considered here. This was a top-down assessment based on the above 3,000 t(HM)/year study with some variations to account for process changes and scale, etc. The use of sintered bentonite or vitrified CsSr wastes may possibly increase waste immobilization costs, but is expected to decrease overall waste storage costs life cycle costs (LCC) by increasing CsSr loading and canister diameter and by reducing waste volumes, total canisters, and required storage capacity. However, depending on design these may need periods of forced convection cooling and delayed potential for using passively cooled storage. If Advanced Fuel Cycle Initiative (AFCI) does call for CsSr separation, a vitrified CsSr waste form option is presently favored

with a range of increased loading values being examined and this makes good use of state-of-the-art vitrification and waste storage technologies.

There was a third conceptual design, which was based on a high temperature, molten salt electrochemical process. This design was based on oxide fuel electrochemical reduction, uranium electrorefining, and transuranic product recovery by electrowinning. The design throughput is 300 t(HM)/year mixed LWR fuel of 60 GW(t).d/t and the process formed a variety of products and wastes including a glass-ceramic CsSr waste formed with zeolite used as an ion exchange material to recover CsSr from salt. The specific activity of this waste form is expected to be similar to or lower than the aluminosilicate. However, the electrometallurgical CsSr waste may have higher radioactive impurity levels (e.g., TRU).

In summary, the CsSr-Rb-Ba separated waste stream from UREX+ aqueous separations is salt free and can be decomposed thermally to the oxides and converted into a wide variety of waste forms and chemistries including particulate ceramics, cements, sintered ceramics, glass ceramic composites, and cast vitrified waste. The waste stream has few process additives so the CsSr waste form may be made as concentrated in CsSr as desired consistent with chemical, physical, and thermal waste-form properties. The Integrated Waste Management Strategy (IWMS) presently favors the CsSr vitrified waste option using existing waste storage and state-of-the-art vitrification technologies. Incorporation of 20% wt CsSrOx in borosilicate glass has been reported and fully active samples made (Aloy 2007). Pacific Northwest National Laboratory is understood to be investigating higher incorporations, ≥40% wt. CsSr-Rb-BaOx, which equates to ≥27% wt CsSrOx. CsSr concentrations in commercial LWR vitrified waste are around an order-of-magnitude lower than the latter number so that borosilicate glass (BSG) waste container diameters may be need to be reduced from 0.4 m to 0.13 m (i.e., by factor $\sqrt{10}$), or SNF decayed stored for >3 CsSr half-lives (i.e., ~100 years). Additionally, increasing the glass transition temperature by several hundred degrees centigrade may allow the canister diameter to be increased back to around 0.2 m with the same high CsSr incorporation. Glass formulations with higher devitrification temperatures generally require formulations with higher melting point as may be achieved by a cold crucible melter.

G1-2.3   Vitrification and Storage of LWR Oxide HLW

For LWR fuels, the main operating commercial separations plants in the world are UP2-800 and UP-3 at Cap La Hague (successful continuous operation) and THORP at Sellafield until 2018. (Rokkasho is believed to start full operation in 2018 and uses Japanese joule –heated ceramic melter vitrification technology). These French and UK plants have used French AVH vitrification technology for nearly 2 decades. Calcined fission product waste is mixed with glass frit in the ratio of around 1:3 by weight. The PUREX raffinate has low processing inerts and after calcination is mainly FP and minor actinide (MA) oxides with very low U, Pu content, and moderate corrosion product concentrations.

Vitrification of commercial and/or defense HLW has taken place at Cap La Hague and Marcoule in France, Sellafield in the UK, Tokai in Japan, Karlsruhe in Germany, Savannah River, West Valley in U.S., Tarapur in India, Russian Federation, etc. Almost all of these facilities use air-cooled vault storage systems where waste canisters are stored in cooled thimble tubes. Most use forced air convection, at least initially, whereas one uses natural convection with forced convection as standby during early operation (IAEA 1992).

France first performed vitrification operations in the 1970s in the Ateliers Vitrification Marcoule facility (known as the AVM) and then in the late 1980s in the R7 and T7 facilities of the La Hague plant (referred to as the AVH). French vitrification technology uses a rotary calciner feeding a metallic inductively heated melter vessel, which siphons batches of vitrified waste into HLW canisters. The Marcoule vitrified waste store used HLW canisters of dimensions, 0.5 m diameter and 1 m height, for lower burnup, lower decay power gas-cooled reactor wastes. For AVM, three casts of glass (120 kg each)

totaling about 140 L are made into a single stainless steel canister. The vitrified waste store used thimble tubes (steel sleeves with base set into concrete) and stacked canisters, 10 high. The sleeves are 0.6 m diameter and 10 m height. The maximum output of the ten canisters in a sleeve is 8 kW (i.e., 0.8 kW/canister) on average, but 1 kW peak value. Forced convection cooling air normally flows between sleeves and canisters at velocities of 10–15 m/s with filtration at outlet but can revert to natural convection without filtration for power failure conditions or after long storage, etc. Two vaults were built initially at Marcoule, one with 80 storage sleeves and the other with 60 storage sleeves. The maximum heat load of the whole store is 1 MW. One AVM single line plant was constructed in the 1970s at Marcoule, to provide vitrification of low burnup gas reactor fuel with vitrified waste power densities of ≤8 W/L.

The AVH stainless steel canisters are cylindrical with overall dimensions of around 0.42 m diameter (17 inches) and height 1.3 m (52 inches). The canisters have a top flange of reduced diameter with welded closure following filling with two pours from the melter. After pouring, the canisters contain about 400 kg (150 L) vitrified HLW and are around three-fourths filled. (In France, the residual space is filled with pucks of compacted leached fuel hulls.) Two AVH plants, designated R7 and T7 and each of three vitrification lines, were constructed in the late 1980s at La Hague, to provide vitrification of standard LWR fuel (33 GW(t).d/t) HLW after 4 years of cooling. Preliminary evaluations foresaw glass center line temperatures ≤650°C and power densities of ≤60 W/L, which implied a maximum canister heat load of 9 kW. Eventual design values were specified as 20 W/L and 3 kW, respectively.

The Sellafield waste vitrification plant was constructed with two AVH process lines, and first operated in the early 1990s. Its VPS accommodates up to 8,000 AVH canisters stacked 10 high (about 13 m). Each canister (400 kg waste) typically contains vitrified waste from the recycling of 8 t Magnox fuel or 2 t oxide fuel (Dobson and Phillips 2006). There are 800 stainless steel storage thimble tubes into which the canisters are stacked through top plugs and seals. Each storage tube is within a rectangular compartment to guide cooling air. Decay heat is removed by natural convection cooling of the exterior of the sealed storage tubes, and due to multiple barriers and compliance with glass centerline limits and civil structural limits, no filtration of the cooling air is required. The Sellafield borosilicate glass formulations have waste oxide incorporations in the range 20–30 wt% with glass transformation temperature of around 550°C; 500°C is taken as the glass center line temperature limit. VPS has capacity for vitrified HLW from two decades of THORP design throughput of 800 t(oxide SNF)/year, that is 16,000 t(oxide SNF) equivalent.

British Nuclear Fuels plc (BNFL) commenced active commissioning of the third line at its Waste Vitrification Plant (WVP) at Sellafield in January 2002. The start of operation of the 320M UK pound (~2000 m.v.) ≡ U.S. $485M (2000 dollars) line enables BNFL to meet its commitment to speed up the conversion of liquid HLW to borosilicate glass blocks for longer term storage. The UK regulator requires year-on-year reductions in highly active liquid waste down to buffer stocks of 200 m^3 by 2015.

The operation of WVP has led to the production of over 4,000 containers of vitrified waste to-date, which are currently stored within the VPS at Sellafield. The VPS is deemed suitable for this interim storage requirement, subject to regular maintenance and refurbishment, for at least 100 years. A proportion of the vitrified HLW will be returned to overseas customers at the appropriate time as set out in the recycling contracts. The canisters of vitrified HLW are kept in a purpose-built store (VPS), which has passive cooling and a back-up forced cooling system.

The design and operation of HLW vitrification facilities has been well described for the major national nuclear programs (IAEA 1992). Following filling of stainless steel, cylindrical waste canisters with vitrified waste, various operations are used to prepare canisters for storage and ultimate disposal. Thermal conditioning of canisters to reduce heat shock and decrease glass cooling rate and fracture may be used. Tungsten Inert Gas (TIG), plasma torch, or upset-resistance welding is used to seal the canisters

with lids. Canister welds are normally inspected optically or by helium leak testing. Canister dimensions, weight temperature and dose rate may be determined. The exteriors of canisters are often decontaminated using high-pressure water, sand slurries, dry blasting, or electrochemical decontamination. Waste canisters must be cooled in storage to minimize devitrification and maintain store integrity.

Currently, operating and planned interim stores use air cooling of canisters. Air cooling can be achieved by conduction, or natural or forced convection. For some high-specific decay power glasses, forced cooling is combined with natural convection cooling. Canister, waste, and store characteristics for various national facilities are given in Table G1-6.

Table G1-6. Canister and waste parameters for operating vitrified HLW stores.

Facility Cooling	Canister I.D./Height m/m	Glass Mass/ Volume, kg/L	Max Activity GBq α/β	Maximum Canister Power, W	Maximum Power W/kg
AVM France Forced/Natural	0.49 1.0	360 135	3.0×10^7 1.4×10^7	1,000	2.8
R7/T7 France Forced/Natural	0.42 1.34	400 150	1.4×10^5 2.8×10^7	2,980 peak 2,100 average	7.5
WVP–VPS UK Natural	0.42 1.34	400 150	-	*Estimated 2,000*	-
DWPF–U.S. Forced/Natural	0.59 3.0	670	-	<1,000	<0.25
TVF–Japan Forced	0.42 1.0	300 110	1.5×10^7 Combined	1,400	4.7

BNFL WVP with Lines 1 and 2 and VPS has dimensions 64 m long × 38 m wide × 40 m high, which gives footprint of 2,430m^2 (IAEA 1992). The capital cost is estimated as 250M Great Britain Pounds (1990 basis) ≡ \$446M (U.S. 1990 dollars[a]) ≡ 730M (U.S. 2008 dollars[b]). The two stores and access corridor have a footprint of around 25 m × 40 m = 1,000 m^2 (10^4 ft^2) or 40% of WVP footprint. A pro rata capital cost for the VPS is then \$292M (U.S. 2008 dollars) ≡ 146M GBP with a capacity corresponding to 16,000 t (LWR SNF). This corresponds to a facility square foot capital cost of \$29K. Commonly process areas have costs that are several times greater than waste storage areas. So, a value of \$150M (\$15K/ft^2) for the store may be appropriate here, and this is regarded as high although passive cooling favors lower long-term operational costs.

G1-2.4   Defense Waste Processing Facility

The DWPF, located on the Savannah River Site (Figure G1-1), uses vitrification to process waste into a stable glass medium. The project began in 1983 and testing began in 1989. Evolving nuclear safety standards and testing difficulties delayed the start of chemical trials until 1993 and radioactive operations did not begin until March of 1996. This protracted start-up period added significantly to the operations component of the capitalized cost. For the purpose of this report, 1986 was chosen as the activity midpoint. The DWPF is a stand-alone process facility. The technology incorporated at the time of construction was considered new technology. It was built as a government-owned facility; therefore, the cost of money is not applicable. The hardened area of the facility is reported as 150,000 ft^2. The square

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a.   Measuring Worth - Exchange Rates Between the United States Dollar and Forty-one Currencies, http://www.measuringworth.com/datasets/exchangeglobal/result.php

b.   Money values derived using: U.S. Army Corps of Engineers, Civil Works Construction Cost Index System (CWCCIS), Using CWBS Feature Code – 07 Power plant, Appendix A, EM 1110-2-1304, Appendix Revised September 30, 2007.

footage does not include the associated interim storage facility. The facility produces about 250 canisters of glass waste per year.

G1 2.2 CFTC Engineering Alternative Studies

The CFTC Engineering Alternative Studies (EAS and Follow-on Engineering Alternative Studies (FOEAS) used the proven DWPF technology concepts used to develop HLW treatment alternatives for various alternatives. These alternative included concepts for the disposal of HLW from:

- 3000MT/yr UREX+1 reprocessing facility (Cs and Sr not incorporated in the borosilicate glass)

- 800MT/yr UREX+1 reprocessing facility (Cs and Sr not incorporated in the borosilicate glass)

- 800MT/yr co-extraction (Co-Ex) reprocessing facility (Cs and Sr are included in the borosilicate glass)

- 300MT Electrochemical reprocessing facility in which the Cs/Sr/I and excess chloride salt are incorporated into a glass bonded zeolite and the lanthanides are incorporated into a lanthanide glass.

G1-3.   PICTURES AND DIAGRAMS

Figure G1-1. Defense waste processing plant at the Savannah River Site.

G1-4.   MODULE INTERFACES

Module G1 receives HLW from Aqueous Reprocessing (Module F1) or Electrochemical Reprocessing (Module F2/D2), conditions the waste (stabilizes to form a durable product such as glass), provides interim storage of the treated waste, and packages the waste in a canister for transport to a Geologic Repository (Module L), Long-term Monitored Retrievable Storage (Module I), or Storage of Recycled Products (Module E4) for advanced reprocessing. Management of HLW in wet or dry bulk interim storage between reprocessing and the conditioning described in this module (e.g., a tank farm) is not included in this module. No transportation or disposal costs are included in this module.

As stated above, all streams from processing used fuel could be potentially classified as HLW under current regulations. In the United States, this is a functional rather than characteristic designation. Also in the United States, wastes from defense related nuclear activities that are not HLW that contain ≥ 100 nCi/g TRU are "TRU wastes," and the WIPP repository for these wastes is restricted to receiving waste derived from defense materials. These same waste characteristics from commercial nuclear operations

would be considered GTCC LLW. Commercial wastes not designated as HLW are LLW, and the numerical limits designating disposition requirements for Classes A, B, and C, and GTCC are defined in 10 CFR 61 and described in detail in Submodule G3 on LLW. Though these wastes are relatively well defined based on characteristics, the disposition pathway for GTCC waste, a geologic repository, has not yet been designed or designated. Thus, for the purposes of this report, it is assumed that the regulations will be reevaluated and changes will allow some of the disposition options shown in Table G1-2. In summary, these changes may include:

1. Consideration of useful radionuclides for recycling, including limits on allowable contaminants.

2. Expansion of the technical bases for the HLW repository license to include additional HLW forms other than borosilicate glass based on performance of the material in standardized tests.

3. Expansion of the WIPP repository capacity and license, or development of a new WIPP like repository for commercially derived GTCC wastes, including reevaluation of the 100 nCi/g limit, and disposition of wastes contaminated to greater than background levels but less than 100 nCi/g TRU.

4. Designation of a repository or other routine disposal pathway for GTCC not requiring a case-by-case performance assessment.

5. Consideration of the concept of "decay storage": secure storage facilities to allow problematic radionuclides such as cesium, strontium, tritium, and noble gases to decay to LLW limits. These materials must be stored for several hundred years isolated from the biosphere and protected against unregulated use.

Costs for each of the major classes of waste are estimated in their respective sections of the report. The criteria for assigning waste classifications are assumed to be consistent with current regulations with no distinction between defense and commercial origin.

Vitrification is used as the HLW baseline because it is the most well-characterized. However, conversion of waste chloride salts to a glass-bonded ceramic, and metalliferous wastes to a metal ingot have been demonstrated on small scales for the electrochemical processing program, and preliminary data packages have been submitted to DOE-Office of Civilian Radioactive Waste Management. Iron-phosphate glasses could be produced using technology similar to current vitrification technology, and Synroc can be made using a hot-isostatic press or a cold-crucible melter, all of which have been published in the literature (Begg et al. 2005; Day et al. 2003; Kim and Hrma 1996; Nicaise et al. 1999). Less well characterized are durable low-temperature ceramics, anionic waste forms for iodine and technetium, crystalline waste forms for noble gases, and steam reforming. Steam reforming is a mid-range high-temperature technology that can destroy organic contaminants and nitrates and convert the inorganic residuals to a mineral form. This type of approach could be particularly useful for some of the streams from aqueous processing that are produced in an organic form such as cesium and strontium. Conversion of this type of material to a durable crystalline form using steam reforming with clay and carbon additives is believed to be possible, but has not been verified at an engineering scale.

G1-5.   SCALING CONSIDERATIONS

Using data from the CFTC studies (see G1-6) the cost was fitted using the logarithmic relationship:

$$CostofA = CostofB \left(\frac{CapacityofA}{CapacityofB} \right)^n$$

Where, capacity is expressed as instantaneous design capacity (MT/yr), and the exponential factor is typically in the range of about 0.6. However due to the inherently high structural costs associated with highly shielded and remotely operated nuclear facilities not found in commercial operations, the power law exponent is expected to be less than 0.6. The preceding equation indicates that a log-log plot of the

capacity versus cost should be a straight line with the slope equal to the exponent. The CFTC HLW vitrification estimates were used to determine the power law factor was equal to about 0.43 over the range of reprocessing facility capacity of 3000MT/yr to 800 MT/yr.

G1-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

G1-6.1 Defense HLW Solidification and Packaging

The total project cost for DWPF including the first two melter replacements is estimated to be about $2.6B in 2006 dollars,[c] (capitalized cost of the facility was $1.5B in 1986 dollars). The current year operating budget is $140M and planned operation is for 25 years.[d] Initially, the facility was designed to produce about 7,000 canisters, but is now planned to produce 6,000 canisters. This increase in efficiency drives the cost per canister up because capital costs are fixed. A simple life-cycle analysis reduces the calculation to:

- Cost per canister = ($2.6B + $140M/yr × 25 yr + D&D)/(6,000 cans) = $1.02M/canister + D&D

- Rounding up to $1.1M/canister would allow $500M for two more melters and decontamination and decommissioning (D&D).

- Per canister cost can be converted to a fission product basis with certain assumptions. As described above, the future reprocessing design has not yet been specified, but a conservative estimate can probably be assumed to be the PUREX baseline. Presumably a new reprocessing design would not be adopted if it generated more waste.

Assuming:

HLW from processing defense fuels is predominantly reprocessing chemicals contaminated with <1 wt% FPs.

FPs include a broad range of elements, but for simplicity assume 50% each Cs-137/Sr-90.

Glass product contains 33.3% HLW oxides.

Canister contains 1800 kg of HLW glass.

Therefore,

1 kg FP = 1.118 kg FP-oxides (Cs2O and SrO)

1 kg FP = 1.118 kg FP-oxides/(0.01 kg FP-oxides/kg HLW-oxides)/(0.333 kg HLW-oxide/kg glass)

1 kg FP = 339 kg glass = 339 kg glass/(1,800 kg glass/canister) = 0.188 canister

1 kg FP = 0.188 canister × $1.1M/canister = $207K/kg FP.

Thus $207K/kg FP is the reference case. However, the DWPF was designed for a particular mission, to vitrify Savannah River HLW in a 25-year life. If the DWPF lifetime is extended to process new HLW, these costs drop, and the incremental costs for more canisters result in the following: annual operating cost/canister production = $140M/250 canisters = $560K, or $105K/kg FP roughly half the baseline cost using the limited DWPF programmatic design life. Recalculating the entire basis, amortizing using a 50-year design life, producing 250 canisters per year yields:

Cost per canister = ($2.6B + $140M/yr × 50 yr + 8 melters × $80M/melter changeout + $500M D&D)/(50 × 250 cans) = $860K/canister, or $162K/kg FP.

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c. This $2.6B figure includes the full cost of the facility operations staffing during the protracted start-up. Using today's accounting practices for the OPC component, the TPC would have been $1.3B in 1993 dollars.

d. Telecon and email with Brent Boore and David McGuire, Savannah River Site, January 2006.

The total project cost (TPC) and annual operations cost cited above present an extremely conservative estimate. The TPC of $2.6B includes the total cost of the operations staffing during the protracted testing and start-up period. Using assumptions similar to today's estimating guidelines the TPC for DWPF would have been $1.3B in 1993. Annual operations cost have continued to drop after start-up and are currently about $90M/yr in 2007 dollars. Using these figures a more reasonable unit cost for 50 years of operation is ($1.3B + $90M/yr × 50 yr + 8 melters × $40M/melter changeout + $500M D&D/(50 × 250 cans) = $530K/canister or $100K/kg of fission products.

Assuming (a) commercialization of new technology for processing used nuclear fuels, (b) many of the problematic radionuclides are partitioned, and (c) the regulatory changes described above, it is likely that scale-up and market forces will drive these costs down. Further, assuming a glass waste form with the same nominal density, but a glass technology that would allow melting at a higher temperature to enable higher waste loading, a glass containing 50 wt% HLW oxides could be possible (Day et al. 2003 and Hrma et al. 1999). If the waste contained 50 to 100% radionuclide oxides as envisioned in the UREX flowsheet, the processed waste form would contain 50% × (50 to 100%) = 25 to 50% radionuclides, versus 1% ×33.3% = 0.33% used above in the baseline or 75 to 150 times more radionuclides per unit of glass. Thus, with $530K/canister operating cost, on the low end the HLW stabilization costs could be:

0.188 canister × $530K/canister/(75 to 150) = $670 to 1,330/kg FP.

More conservatively, it could be assumed that maximum radionuclide loading is limited to about 5%, but the facility costs remain at $530K/canister of the resulting unit cost is:

0.188 canister × $530K/canister/(5/.33) = $6,600/kg FP.

G1-6.2   CFTC Fission Product Solidification and Storage Estimates

The CFTC EAS and FOEAS developed HLW treatment alternatives for various alternatives. These alternative included concepts for the disposal of HLW from:

- 3000MT/yr UREX+1 reprocessing facility (Cs and Sr not incorporated in the borosilicate glass)

- 800MT/yr UREX+1 reprocessing facility (Cs and Sr not incorporated in the borosilicate glass)

- 800MT/yr Co-Ex reprocessing facility (Cs, Sr, Am and Cm are included in the borosilicate glass)

- 300MT Electrochemical reprocessing facility in which the Cs/Sr/I and excess chloride salt are incorporated into a glass bonded zeolite and the lanthanides are incorporated into a lanthanide glass.

The cost estimates for these alternatives are provided in Table G1-3. These cost estimates are for the HLW vitrification segment of the CFTC, they do not include the costs of volatile off-gas capture and treatment, cesium/strontium solidification and packaging, or technetium conversion to metal and packaging in cases where those processes are applicable. See below for cost estimates of the Cs/Sr and Tc solidification.

The data presented in Table G1-3 for the 3000MT/yr reprocessing alternative has been adjusted from that presented in the reference documents (WSRC 2007). Adjustments were made to ensure the assumptions and design attributes were consistent with the 800MT/yr cases. These adjustments include the elimination of sand filters and inclusion of additional footprint for HEPA filters, a reduction in the hardened footprint to reflect an optimized canyon equipment arrangement developed as a part of the FOEAS, and elimination of future project cost from the LCC to reflect a consistent assumption that waste disposal facilities were available such that multiple waste glass storage buildings were not required.

The Sensitivity Analysis 5 (SA5) or Co-Ex case is slightly higher than the UREX+1 due to the inclusion of both Cs/Sr and Tc in the glass waste form. The overall reprocessing cost of the Co-Ex process is less than the cost of the more complex UREX+1 processes, which offer potential advantages in waste disposal costs.

Table G1-3 also provides the resulting unit cost on a basis of $/kg of fission products and $/MT of SNF being reprocessed. The later value must be added (including others such as LLW packaging and treatment and uranium solidification and packaging) to the unit cost of reprocessing to obtain a comparable number to those often sited in the literature and other studies for the total unit cost of reprocessing.

The 3000 MT/yr case is somewhat less on a unit cost basis reflecting the economy of scale expected for these treatment processes.

An initial 5-year waste storage capacity is provided in the estimates. Long-term decay storage may be planned for some case studies. A storage vault with a 1,400 storage locations is required every 5 years during recycling operations and has an estimated TPC range of $60M to $85M and an annual Operations and Maintenance (O&M) cost of $9M to $14M/yr. Assuming a 40-year operation, seven additional vaults will be required. If the glass is allowed to cool for 100 years before shipment then the total additional LCC is approximately $1B to $1.4B or an additional $800 to $1,200/kg FP.

Table G1-3. CFTC TPC and LCC estimates for HLW vitrification.

Millions of 2007 Dollars	Benchmark 1 3000 MT/yr UREX+1		Benchmark 2 800 MT/yr UREX+1		SA5 800 MT/yr Co-Ex		Benchmark 3 300 MT/yr Electrochemical	
	Low	High	Low	High	Low	High	Low	High
Annual Operations Cost (Nominal Year) Labor	41	62	34	50	40	60	33	49
Utilities	9	13	3	5	4	7	5	7
Materials	4	6	4	6	4	5	3	5
Misc. Contracts	1	1	1	1	1	1	0	2
Misc. Projects	3	4	3	4	3	4	3	3
Total Annual Operations Cost	58	86	45	66	52	77	44	65
40 Year LCC								
Labor	2,175	3,259	1,722	2,583	2,008	3,012	1686	2528
Materials	213	319	184	276	192	288	191	286
Utilities	452	678	168	251	227	340	245	368
Contracts	40	67	32	47	43	64	33	50
Misc. Projects	113	166	93	140	112	168	93	140
Subtotal: 40-Year Operations	2,993	4,489	2,198	3,297	2,581	3,872	2,248	3,372
Future Capital Projects	0	0	0	0	0	0	0	0
D&D	582	825	303	431	343	541	20	34
Subtotal LCC O&M & D&D	3,575	5,314	2,502	3,729	2,924	4,414	2,268	3,406
Early Life Cycle	46	54	36	51	55	85	6	10
TPC	4,434	6,175	2,594	3,593	3,030	4,482	148	237
Total LCC	8,055	11,544	5,132	7,373	6,009	8,981	2,422	3,653
Unit LCC Cost ($/kg FP)	1,804	2,586	4,277	6,144	3,964	5,921	12,015	18,122
LCC Unit Cost ($/MT SNF) [0% discount rate]	67	96	160	230	188	281	202	304
Values may not add due to rounding								

G1-6.3   CFTC Tc Separation and Solidification Estimates

The CFTC EAS developed estimates for the separation of the Tc from the uranium nitrate solution using an ion exchange process. The resin was loaded and pyrolyzed to reduce the Tc to a metallic form. The cost estimates shown in Table G1-4 do not include the cost of combining the Tc with a portion of the Zr hulls and production of the metal alloy. These later functions were conducted in the fuel receipt and dissolution building and their cost are an integrated part of the reprocessing module (F-1) costs.

The data presented in Table G1-4 for the 3000MT/yr reprocessing alternative has been adjusted from that presented in the reference documents (WSRC 2007). Adjustments were made to ensure the assumptions and design attributes were consistent with the 800MT/yr cases. Table G1-4 also provides the resulting unit cost on a basis of $/kg of Tc and $/MT of SNF being reprocessed. The later value must be added to the unit cost of reprocessing to obtain a comparable number to those often sited in the literature and other studies for the total unit cost of reprocessing.

The 3000 MT/yr case is somewhat less on a unit cost basis reflecting the economy of scale expected for these treatment processes.

Table G1-4. CFTC TPC and LCC estimates for Tc separation and solidification.

Millions of 2007 Dollars	Benchmark 1 3000 MT/yr UREX+1		Benchmark 2 800 MT/yr UREX+1		SA5 800 MT/yr Co-Ex		Benchmark 3 300 MT/yr Electrochemical	
	Low	High	Low	High	Low	High	Low	High
Annual Operations Cost (Nominal Year) Labor	37	56	24	35	Not Applicable		Not Applicable	
Utilities	8	12	2	3				
Materials	4	5	3	4				
Misc. Contracts	1	1	1	1				
Misc. Projects	3	4	2	3				
Total Annual Operations Cost	**52**	**78**	**31**	**46**				
40 Year LCC								
Labor	1973	2956	1209	1813				
Materials	193	290	129	193				
Utilities	410	615	118	176				
Contracts	36	60	22	33				
Misc. Projects	103	151	65	98				
Subtotal: 40-Year Operations	**2,715**	**4,072**	**1,543**	**2,314**				
Future Capital Projects	0	0	0	0				
D&D	247	344	162	225				
Subtotal LCC O&M & D&D	**2,962**	**4,416**	**1,704**	**2,539**				
Early Life Cycle	19	23	19	27				
TPC	1,884	2,571	1,384	1,879				
Total LCC	**4,866**	**7,009**	**3,107**	**4,445**				
Unit LCC Cost ($/kg FP)	32,491	46,805	161,836	231,496				
LCC Unit Cost ($/MT SNF)	41	58	97	139				
Values may not add due to rounding. Unit costs based on 0% discount rate.								

G1-6.4   CFTC Cs/Sr Solidification, Packaging and Storage Estimates

The CFTC EAS developed estimates for the solidification and packaging of the cesium and strontium (rubidium and barium is also included). Benchmark 1 used the sodium aluminosilicate process to form a ceramic, while Benchmark 2 used the bentonite clay process to form a ceramic wasteform. The use of two different processes at two different capacities makes comparison of the data difficult.

The data presented in Table G1-5 include the cost to solidify, package, and store the waste for 3 years. Additional storage is required if the waste is to be decayed at the reprocessing site.

Table G1-5 also provides the resulting unit cost on a basis of \$/kg of Cs/Sr and \$/MT of SNF being reprocessed. The later value must be added to the unit cost of reprocessing to obtain a comparable number to those often sited in the literature and other studies for the total unit cost of reprocessing.

Table G1-5. CFTC TPC and LCC estimates for Cs/Sr solidification, packaging and storage.

Millions of 2007 Dollars	Benchmark 1 3000 MT/yr UREX+1		Benchmark 2 800 MT/yr UREX+1		SA5 800 MT/yr Co-Ex		Benchmark 3 300 MT/yr Electrochemical	
	Low	High	Low	High	Low	High	Low	High
Annual Operations Cost (Nominal Year) Labor	59	88	38	56	Not Applicable		Not Applicable	
Utilities	12	18	3	5				
Materials	6	9	4	6				
Misc. Contracts	1	2	1	1				
Misc. Projects	4	6	3	4				
Total Annual Operations Cost	**83**	**124**	**49**	**73**				
40 Year LCC								
Labor	3114	4666	1907	2861				
Materials	305	457	204	305				
Utilities	648	971	186	279				
Contracts	57	95	35	52				
Misc. Projects	162	238	103	155				
Subtotal: 40-Year Operations	**4,285**	**6,428**	**2,435**	**3,652**				
Future Capital Projects	0	0	0	0				
D&D	480	775	328	533				
Subtotal LCC O&M & D&D	**4,766**	**7,203**	**2,763**	**4,185**				
Early Life Cycle	38	51	39	63				
TPC	3,659	5,802	2,804	4,441				
Total LCC	**8,462**	**13,056**	**5,606**	**8,689**				
Unit LCC Cost (\$/kg Cs/Sr)	12,329	19,021	30,700	47,600				
LCC Unit Cost (\$/MT SNF)	71	109	175	272				
Values may not add due to rounding. Unit costs based on 0% discount rate.								

An initial 4-year waste storage capacity is provided in the estimates. Long-term decay storage may be planned for some case studies. Due to the different wasteform properties the storage costs for the two processing options varied significantly. The wasteform produced by the sodium aluminosilicate process is a finely divided powder and a relatively high (10%) Cs/Sr waste loading. The heat transfer properties of the power combined with the high decay heat resulted in 3-inch-diameter storage containers. For this case a storage vault with a 30,000 storage locations is required every 2 years during recycling operations and has an estimated TPC of \$390M to \$620M and an annual O&M cost of \$15M to \$23M/yr. Assuming a 40 year operation 18 additional vaults will be required. If the ceramic is allowed to cool for 300 years

before shipment then the total additional LCC is approximately \$11.0B to \$17.2B or an additional \$15,900 to \$25,000/kg FP.

The wasteform produced by the bentonite clay process is pucks that are then stacked into approximately 9-inch-diameter canisters. For this case a storage vault with a 1,400 storage locations is required every 5 years during recycling operations and has an estimated TPC of \$170M to \$275M and an annual O&M cost of \$11M to \$17M/yr. Assuming a 40 year operation seven additional vaults will be required. If the ceramic is allowed to cool for 300 years before shipment then the total additional LCC is approximately \$4.0B to \$6.3B or an additional \$22,200 to \$34,800/kg FP.

G1-7.   DATA LIMITATIONS

The DWPF reported costs are gross numbers based on a one-of-a-kind facility for processing defense HLW. The CFTC studies for the treatment of aqueous waste are based on a borosilicate waste form (the worldwide standard for HLW) and currently understood technological limits. The CFTC study for the electrochemical HLW treatment is a ROM estimate as many of the processes required have not been demonstrated at a commercial scale. Future reprocessing concepts for commercial fuels may generate entirely different waste forms including glass-ceramics, metal ingots, and pressed ceramic pucks. It can probably be assumed that a transition to a new waste form would be driven by efficiency in terms of greater fission product loading (10 to 100 times or more), which could drive costs down (for stabilization and the repository, but not necessarily for the entire life-cycle). If multiple waste forms are produced then additional capital and operating costs will be incurred. Assuming that all the separations are successful, the HLW form would only be limited by durability and not heat loading or criticality. Further, waste-form manufacture may be integrated with the reprocessing plant rather than in a dedicated facility, which should also drive cost down. Lastly, future processing scenarios envisioned include many different product streams with a significantly reduced HLW volume, as described above. This may drive the unit costs for HLW forms up due to fixed facility costs, but the ratio of HLW to metric ton of heavy metal (MTHM) processed should be reduced enough to more than compensate, reducing overall waste management costs.

G1-8.   COST SUMMARIES

The module cost information is summarized in the WIT cost summary in Table G1-6. 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.

New fuel processing flowsheets are being developed to generate far less waste volume, and to segregate problematic radionuclides. It is also widely recognized that many waste forms are as durable or better than single-phase BSG in containing radionuclides for extended times in exposure to the environment. Based on this and knowing that much higher waste loading is attainable in other materials significant reduction in cost (10–100X) may be attainable for HLW stabilization by cutting operation costs and using much more efficient waste forms and stabilization technology. However, the costs of the vitrification facility at Hanford are currently under review, and little is known about large-scale production of some of the proposed waste forms such as glass-ceramics and metal ingots, so the potential reduction in costs may be nearer the low end of this range. The selected value is based on the value from the CFTC study for a vitrification facility integrated into a reprocessing facility with a nominal capacity of 800 MT/yr using a reasonably aggressive waste loading of 15%.

Table G1-6. Cost summary "What-It-Takes" (WIT) table for HLW conditioning selected values.

Reference Cost(s) Based on Reference Capacity	Low Cost	Mode Cost	Mean Cost	High Cost
HLW Borosilicate Glass				
	$2,200/kg FP	$5,000/kg FP		$6,600/kg FP
Escalated Year 2020$ **(G1-1A)**	$2,600/kg FP	$6,000/kg FP	$5,500/kg FP	$7,900/kg FP
	Unit cost for a 3000MT/yr reprocessing integrated complex with 15% FP loading	Based on an 800 MT/yr reprocessing center with 15% FP loading		Based on the DWPF facility with a 5% FP loading
Electrochemical HLW Treatment CFTC EAS				
	$12,015/kg FP	$15,100/kg FP average of the CFTC high/low values		$18,122/kg FP
Escalated Year 2020$ **(G1-2E)**	$14,300/kg FP	$18,000/kgFP	$18,000/kgFP	$21,600/kg FP
U/Tc Separation and Solidification CFTC EAS				
	$161,836 /kg Tc	$200,000/kg Tc average of the CFTC high/low values		$231,496 /kg Tc
Escalated Year 2020$ **(G1-2A)**	$193,100/kgTc	$238,600/kgTc	$236,000/kgTc	$276,200/kgTc
Cs/Sr Solidification and Packaging **(G1-3A)**	$36,600/kg Cs/Sr	$47,700/kg Cs/Sr	$47,000/kg Cs/Sr	$56,800/kg Cs/Sr
	Low unit cost of a bentonite clay ceramic process integrated into an 800MT/yr reprocessing center	High unit cost of a bentonite clay ceramic process integrated into an 800MT/yr reprocessing center		Average unit cost of a bentonite clay ceramic process integrated into an 800MT/yr reprocessing center

The triangular distributions based on the WIT Table are shown in Figure G1-2. Some distributions are skewed toward the high cost due to the difficulty in achieving fission product loading greater than 10% in the waste form.
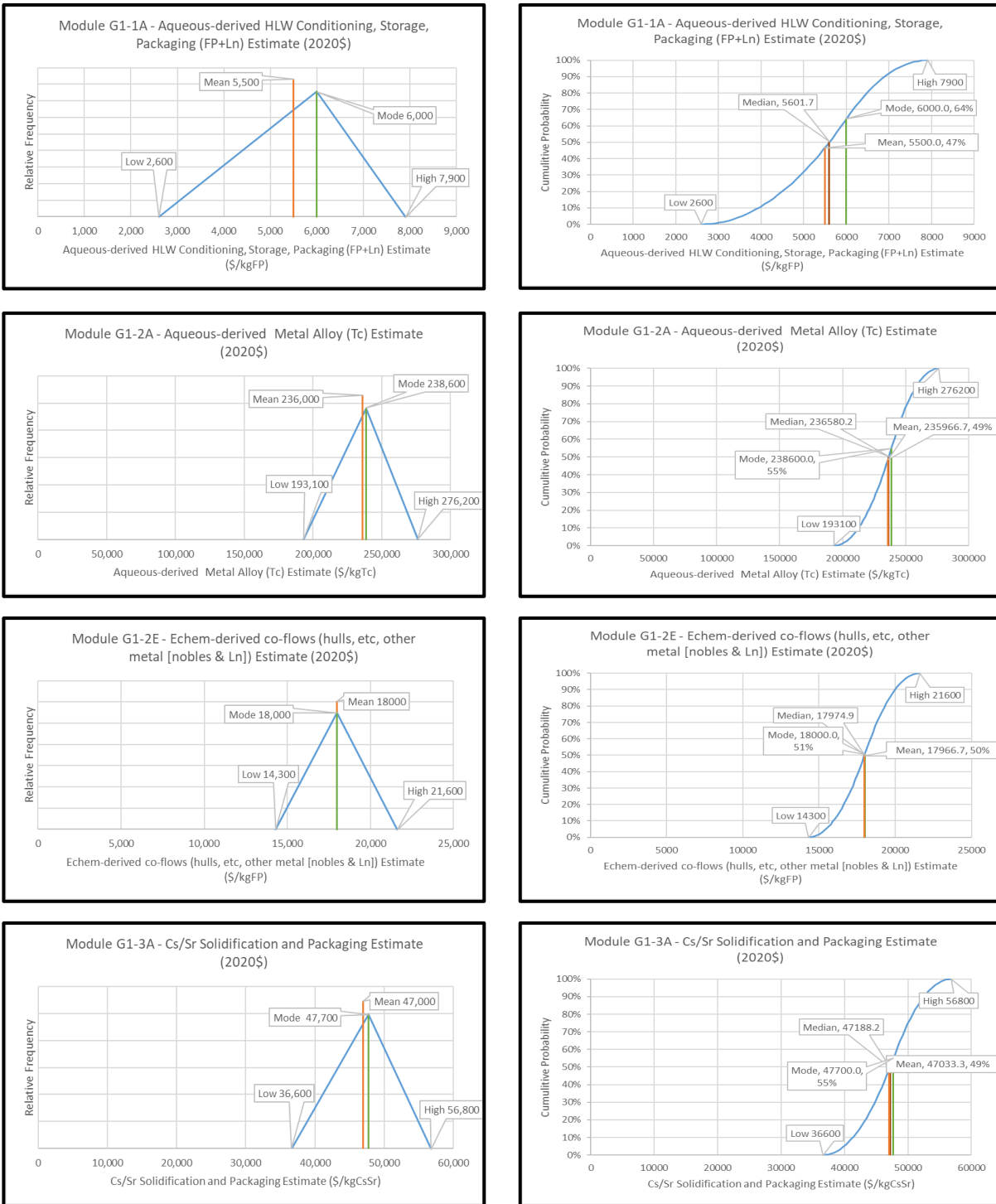
Figure G1-2. HLW conditioning, storage, and packaging estimated cost frequency and cumulative distributions.

G1-9.   SENSITIVITY AND UNCERTAINTY ANALYSES

None available.

G1-10. REFERENCES

See G5-10 and G5-11.

Module G2

SNF Conditioning and Packaging

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G2 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2006	All	Version of AFC-CBR in which Module first appeared: First became separate submodule in 2006. Cost estimates for pre-reprocessing SNF operations were needed.
	2017	All	Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges: 2009. 2006 data was escalated to 2017$ for this latest revision.
			New technical/cost data which has recently become available and will benefit next revision: • New estimates might be available from vendors and from DOE-NE Used Nuclear Fuel campaign cost and schedule studies. Care should be taken that these conditioning and packaging operations (and casks) are not already in cost data appearing in Modules I (centralized dry storage) or L1 (Geologic Disposal of SNF).
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module G2
SNF Conditioning and Packaging

G2-MD.   SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**

- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only from last time (2006) values underwent technical assessment.

- **Estimating Methodology for latest (2009 AFC-CBR) technical update from which this 2017 update was escalated:** 2006 Vendor estimates for conditioning and packaging operations including casks.

G2-1.   BASIC INFORMATION

The SNF packaging module includes capabilities to safely remove SNF from wet or dry storage; perform inspection as required; and dry, package, seal, leak-check, and prepare the SNF package for shipping to reprocessing, storage, or disposal. Fuel is assumed to be in wet or dry interim storage at a nuclear facility, and a contractor is hired to provide packaging services. The contractor will interface with site personnel to receive fuel from interim storage and conduct all operations necessary to leave the fuel in stable dry storage at an onsite storage pad. Transportation offsite is covered in Module O.

In the future, these costs are envisioned to be routine, and could be part of the general maintenance and fueling of a commercial reactor. The costs are delineated here to estimate the burden on current nominal operating costs. Whether the actual costs are born by the reactor operator as part of operating costs, or are a part of the fee paid to the Nuclear Waste Fund is not defined.

G2-2.   FUNCTIONAL AND OPERATIONAL DESCRIPTION

Fuel will be removed from wet or dry interim storage, conditioned for indeterminate storage, packaged, and left in a protective cask at the storage site. All fuel movement procedures and equipment will be designed to ensure criticality-safe conditions at all times. Facility procedures will ensure verification and visual inspection of all lifting equipment and heavy load handling procedures. Fuel assemblies selection will be verified to ensure only fuel assemblies approved for loading in a fuel storage container are loaded. Inspection will include verification of the condition of the fuel to ensure it is acceptable for packaging, including integrity of fuel rods and replacement of any removed rods to ensure configuration control.

Drying procedures will meet or exceed the methodology described in NUREG 1536 (NRC, 1997) and be in compliance with the facility Safety Analysis Report. Moisture will be removed from the cask and container until vacuum can be maintained for the prescribed test period. Seal welding will of the multipurpose canister will meet all prescribed nondestructive examination tests. Transportation and storage casks and multipurpose canisters will be licensed by the NRC.

In general, the contractor will:

1. Bring a fuel container (container, basket) and a shielded transfer cask to the fuel pool

2. Place the container into the transfer cask, forming concentric cylinders

3. Fill the assembly with water and lower into the fuel loading pool

4. Place preselected fuel elements into the container compartments

5. Place a shielded plug in the top of the container

6. Move the loaded assembly to a draining area, then drain and decontaminate

7. Weld the container shut by an automated machine

8. Apply a vacuum to the container while it is filled with an inert gas (helium)

9. Continue the vacuum procedure until a vacuum can be maintained, indicating negligible free water remaining

10. Weld the container ports, apply another cap, and weld cap shut

11. Move the loaded transfer cask assembly to the fuel storage pad

12. Lower the sealed fuel container vertically or push horizontally (depending on design) directly from the transport cask into the storage cask, maintaining continuous shielding

13. Place the storage cask lid and bolt shut

14. Store fuel dry indefinitely pending disposition.

G2-3.   PICTURES AND DIAGRAMS

Several configurations are available for SNF packaging, shipment, and interim to long-term dry storage. Examples are shown in Figures G2-1 through G2-5.

Receiving the MPC at J.A. FitzPatrick Nuclear Plant   Fit up of the MPC and MPC Lid at J.A. FitzPatrick Nuclear Plant

Figure G2-1. Holtec International fuel storage canister to be loaded with fuel assemblies. Figure taken from Holtec International Web site.

Figure G2-2. Holtec International cask in fuel storage pool). Figure taken from Holtec International Web site.

Figure G2-3. Holtec International HI-STORM Dry Storage Casks on storage pad (note vertical storage). Figure taken from Holtec International Web site.

Figure G2-4. Transnuclear NUHOMS design (Note horizontal storage allowing stacking) (AREVA 2007).

Figure G2-5. BNG Fuel Solutions vertical cask lift. Figure taken from BNG Web site. (BNG Fuels Solutions was formerly BNFL Fuel Solutions)

G2-4.   MODULE INTERFACES

Module G2 SNF Packaging removes SNF from wet or dry interim storage and prepares it for indeterminate dry Long-term Monitored Retrievable Storage (Module I), and shipping to reprocessing via Aqueous or Electrochemical Separations (Modules F1 and F2/D2), or a Geologic Repository (Module L). Module G2 can be considered more of an activity or service more than a facility. Conditioning and packaging of fuel can be done as a contracted service or an in-house capability, depending on the nature of the facility and whatever strategy is cost-effective. This module does not include shipment of SNF to an offsite facility even if the facility is owned by the utility. Transportation onsite is considered within the estimating error of the conditioning and packaging costs.

This module includes the costs of a multipurpose canister to move the fuel to a storage cask or a shipping cask, but not the cost of the cask itself. Transportation Module O1 includes the cost of the transportation cask (overpack) and impact limiters. The Fuel Storage Modules E1 and E2 include a dry-storage cask where necessary, but do not include the multipurpose canister.

G2-5.   SCALING CONSIDERATIONS

Fuel is removed from the cooling pool and placed in dry storage by a contractor as described above. The dry storage pad may be in an onsite or offsite leased Independent Spent Fuel Storage Installation. The reactor operator will buy the fuel movement and conditioning services and the necessary materials including the fuel container and the storage cask. The only scaling factor is a storage cask, which generally holds 11 to 15 MTHM, depending on the type and design of the fuel (pressurized versus boiling water reactor).

G2-6.   COST BASES, ASSUMPTIONS, AND DATA SOURCES

Commercial services and their costs are generally proprietary, but the following estimates are based on informal vendor communications:

- Service contract labor costs for implementing the procedures above start at $200K/cask

- Capital costs for storage container and dry storage overpack (cask) start at $1M

- Cost per MTHM=($200K/cask loading + $1,000K/container and overpack capital)/(11−15 MTHM)

- Total cost to implement dry storage = $80K−110K/MTHM.

These costs do not reflect the capital or operating costs of the Independent Spent Fuel Storage Installation itself because this module only includes SNF conditioning and packaging.

G2-7.   DATA LIMITATIONS

The cost data reported here are a snapshot in time and reflect the input from one helpful vendor. The estimates are based on a utility having a contract for recurring services, but no economies of scale are considered for operators negotiating for services to multiple sites or multiple reactors. Also, no transportation costs are considered to support an offsite Independent Spent Fuel Storage Installation.

G2-8.   COST SUMMARIES

The module cost information is summarized in the WIT cost summary in Table G2-1. 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 the main section of this report for additional discussion of the cost estimation approach used to construct the WIT table.

Cost data reflect starting prices for services and materials that imply costs can be higher, reflected in the downsides of about 33%. However, many utilities operate plural reactors and plural reactor sites, which may allow for some economies of scale and reduced negotiated contract prices, reflected in the upsides of about 17%. The selected value is the high end of the reference range because of the limited data available.

The triangular distribution based on the costs in the WIT Table is shown in Figure G2-6.

Table G2-1. Cost summary 'What-It-Takes' (WIT) table for SNF conditioning selected values.

Reference Cost(s) Based on Reference Capacity	Low Cost	Mode Cost	Mean Cost	High Cost
$80K–100K/MTHM SNF (2006$)	$50K/MTHM	$100K/MTHM		$130K/MTHM
Escalated to Yr 2020$ (26% increase from 2006 per escalation table) **(G2)**	$60/kgHM	$130/kgHM	$120/kgHM	$160/kgHM
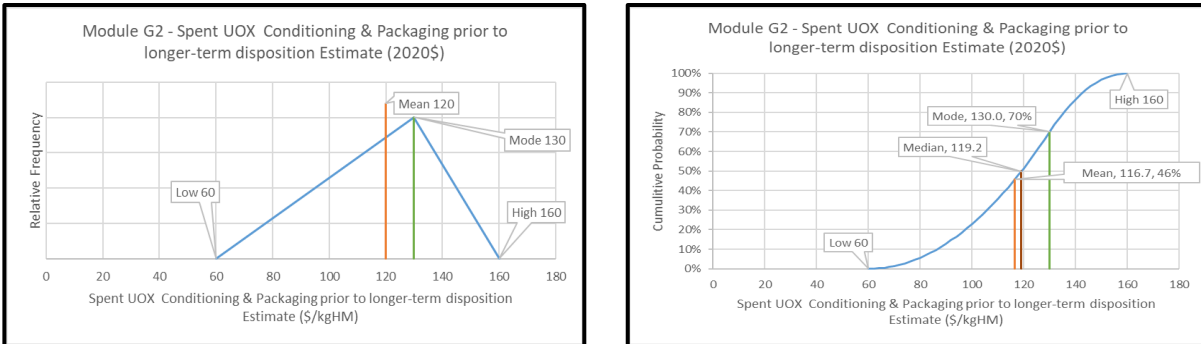
Figure G2-6. SNF conditioning and packaging estimated cost frequency and cumulative distributions.

G2-9.   SENSITIVITY AND UNCERTAINTY ANALYSES

None available.

G2-10. REFERENCES

See G5-10 and G5-11.

Module G3

LLW Conditioning, Storage, and Packaging

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G3 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2006	All	Version of AFC-CBR in which Module first appeared: First became separate submodule in 2006.
	2017	All	Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges: 2006 for all LLW except solids and debris. 2015 data escalated for the latter. 2006 and 2015 data were escalated to 2017$ for this latest revision.
			New technical/cost data which has recently become available and will benefit next revision: New estimates might be available in the future from LLW-handling vendors and perhaps from utility users of these services.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module G3
LLW Conditioning, Storage, and Packaging

G3-MD.   SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**
- **Nature of this FY21 Module update from previous AFC-CBRs: Escalation only from last time values underwent technical assessment:** 2006 for liquid and resin-derived LLW; 2015 for solid LLW (also for solid DU oxides for Module K1)

- Estimating Methodology for latest technical updates from which this FY21 update was escalated: 2006 DOE estimates for commercial LLW handling for materials generated at Government sites. Also data from bottom-up estimate generated for hypothetical Consolidated Fuel Treatment Center (CFTC), one of the first reprocessing studies performed under GNEP. For standard solids and debris LLW, the processing costs were reassessed (2015) when deconversion and treatment costs for DU oxide were reassessed,

G3-1.   BASIC INFORMATION

Module G3 conditions and packages miscellaneous LLW (10 CFR 61) for disposal in an NRC-licensed near surface landfill. If the wastes are both hazardous (40 CFR 261.3) and radioactive, treatment must consider EPA Land Disposal Restrictions (LDRs; 40 CFR 268), and the receiving landfill may be required to have a permit from the EPA and/or state. On a cost per volume basis mixed-waste (toxic and radioactive) treatment and disposal generally cost 2 to 5 times more than LLW because facilities are limited. Currently, mixed-waste treatment/disposal is a seller's market, but this could change in the future, resulting in more consistent pricing based on waste volume.

Wastes are received by truck or rail and must be characterized to ensure that they are within the facility specific permit limits. For example, EnergySolutions in Utah is currently limited to Class A wastes, while Permafix can receive and treat some Class B and C wastes as long as after treatment the treated wastes meet Class A limits and can be sent to EnergySolutions. The regulations, particularly the mixed waste regulations issued independently by the DOE/NRC and EPA can conflict and produce so-called "orphan" wastes for which there are no permitted disposal facilities at this time. Innovation by commercial entities such as the synergy described between Permafix and EnergySolutions have allowed treatment/disposal of many of the orphan wastes, but generally at a cost premium. This is an area that should be considered carefully in support of an expanded nuclear industry. Fortunately, the commercial nuclear industry has carefully evaluated many of their ongoing activities and has all but eliminated production of mixed wastes. Until facilities are decommissioned, production of mixed wastes will be minimal and should not be significant in future commercial nuclear facilities.

G3-2.   FUNCTIONAL AND OPERATIONAL DESCRIPTION

The LLW Conditioning, Storage, and Packaging Facility will likely be a part of future nuclear facilities, but may also be contiguous with the disposal landfill such as the case with EnergySolutions (see Figures G3-1 through G3-4), or may be a separate contracted facility such as the Duratek facility in Tennessee; Pacific EcoSolutions Inc., (PEcoS) in Washington; or Permafix in Florida, that all ship the conditioned wastes to landfills such as Barnwell (see Figure G3-5) in South Carolina or EnergySolutions in Utah . External facilities must be capable of receiving wastes by truck and rail, and must have sufficient analytical facilities or access to such facilities to ensure that the materials they receive are within the limits imposed by their permits. At a minimum, the facilities must be able to inspect and

repackage to meet the waste acceptance criteria for the landfill. Other conditioning and treatment services offered will likely be based on return on investment and local expertise. Some of the more common services include:

- Supercompaction to reduce volume of compressible materials

- Size reduction to reduce volume of oversized materials such as construction debris

- Stabilization using sorbents to immobilize free liquids

- Stabilization using a cement and/or a pozzolonic material to reduce leachability of metals

- Macroencapsulation of debris including lead bricks

- Chemical oxidation for reactive metals and some organics

- Thermal desorption to separate organic constituents from waste matrices

- Incineration to minimize ultimate volume of combustibles or destroy solvents and other organic materials

- Specialized treatability studies and treatment for unique wastes.

G3-3.   PICTURES AND DIAGRAMS

Figure G3-1. Aerial view of EnergySolutions Facility in Utah (EnergySolutions 2009).

Figure G3-2. Filling voids around drums at EnergySolutions Facility in Utah. Figure taken from EnergySolutions Web site.

Figure G3-3. EnergySolutions microencapsulation and macroencapsulation of waste in plastic polymer. Figure taken from EnergySolutions Web site.

Figure G3-4. Landfill disposal cell at EnergySolutions (Note line and leachate collection piping). Figure taken from EnergySolutions Web site.
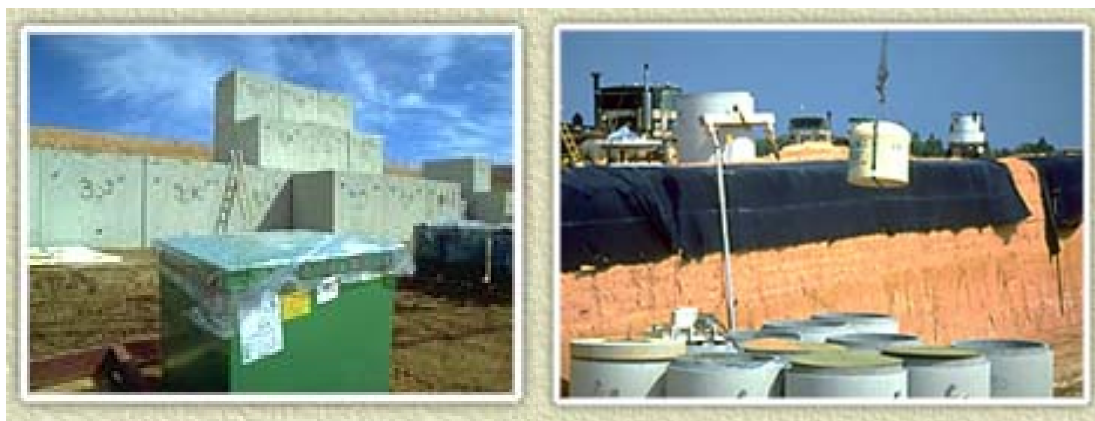
Figure G3-5. Waste placement in landfill at Chem-Nuclear Systems Barnwell (South Carolina) site (Chem-Nuclear Systems, LLC 1997).

G3-4.   MODULE INTERFACES

Module G3 receives miscellaneous low activity waste streams from throughout the fuel cycle. These wastes can be solid or liquid and may result from treatment of gaseous effluents, but the gases themselves are not considered in this module. Specific links are shown from Aqueous and Electrochemical Separations (Modules F1 and F2/D2), but wastes including decontamination solutions, clothing, resins, and so-called combustible rags, bags, and tags wastes may come from any module. All LLW leaving Module G3 is transported (Module O2) to Near Surface Disposal (Module J) once conditioned to meet the shallow geologic disposal facility waste acceptance criteria. Mixed wastes have essentially been eliminated from the commercial nuclear industry by careful selection of materials and waste management. However, mixed wastes are more likely to occur with fuel reprocessing activities generating process and decontamination solutions and spent solvents.

G3-5.   SCALING CONSIDERATIONS

Little or no reliable cost data are available for construction of facilities, and scaling based on throughput is unreliable because of the variable nature of the wastes, site-specific waste acceptance criteria, and conflicting regulations. In general, this type of work can be assumed to be contracted, but for the purposes of this document two reference studies were used, one by the DOE Office of Environmental Management (EM) (Yuracko et al. 2002) and one by the General Accounting Office (GAO) (GAO 2000).

G3-6.   COST BASES, ASSUMPTIONS, AND DATA SOURCES

G3-6.1   Idaho National Laboratory

Idaho National Laboratory (INL) has contracts with several waste treatment and disposal service companies, and these values have been generalized to develop Table G3-1. The costs shown are in 2005 dollars and are subject to change, but provide reasonable factors for estimating the impacts for LLW generated in the fuel cycle. These costs are charges for treatment and disposal at disposal facilities. A rough estimate to include the generator costs for characterization, packaging and shipping would double these costs. The costs shown in Table G3-1 are bracketed by those reported by EM and the GAO. The EM study is an attempt to gather life-cycle costs including both generator and disposal facility costs. The GAO study is limited by the fact that disposal facilities are not consistent in billing practices and do not include full life cycle even for the disposal facilities themselves.

Table G3-1. Treatment/disposal cost estimating factors for LLW.

Waste Type—These wastes can be derived from any module	Media	Characterization/ Pack $/m³	Treatment $/m³	Total $/m³
General LLW Combustible debris	Paper, plastic, cloth, wood	440	N/A	440
General LLW Noncombustible Debris	Metal, construction debris, labware	520	N/A	520
General LLW Liquids	Primarily aqueous solutions requiring stabilization prior to disposal	5,800	5,000	10,800
LLW Water Purification resins	Spent ionic exchange resins – Cs/Sr	5,800	84,000	90,000
General MLLW Combustible Debris	Paper, plastic, cloth, wood	4,000	3,400	7,400
General MLLW Noncombustible Debris	Metal, construction debris, labware	5,500	4,700	10,200
General MLLW Liquids	Typically combustible organic solvents, but may contain significant aqueous fraction	14,000	14,000	28,000
LLW/MLLW	Premium cost per curie of H-3 or C-14	19,000	N/A	19,000

Yuracko, et al.'s 2002 report breaks down costs into disposal facility and predisposal (generator) costs with cost ranges of $70–2000/m³ and $130–4,100/m³ respectively or $200–6,000/m³ total. Disposal costs include charges by the disposal facility itself, which should include management, operations, closure, long-term stewardship, and profit. Predisposal costs include characterization, treatment, packaging, and transportation. Disposal of bulk contaminated soils from Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) cleanup at DOE CERCLA disposal units may bias these values to the low end, and special case wastes of very small volume with unique characteristics are at the high end, with an order-of-magnitude or more between the unit costs for various waste streams. This type of rangeability can also be seen in Table G3-1 with $500–600/m³ for general LLW disposal requiring no special treatment up to $95,000 for volume reduction and disposal of spent ion-exchange resins, a nearly 200 times multiplier.

The U.S. General Accounting Office's 2000 report is somewhat dated in that the Nevada Test Site (now Nevada National Security Site) facility is now accepting mixed wastes and does not include full life-cycle costs for the generator or the disposal facilities, so in general the GAO study shows LLW disposal costs toward the low end of the spectrum at $60–400/m³. This may also be due to the weighted average emphasis on CERCLA wastes going to onsite CERCLA disposal facilities that limits characterization, treatment, and transportation costs. Some wastes at INL are also sent to an onsite CERCLA disposal landfill, but the costs shown in Table G3-1 are for wastes sent offsite. Offsite disposal is more likely representative of the true costs for Module G.

The scope of Module G covers only the costs prior to shipping; for LLW, this is generally characterization and packaging. At the treatment, storage, and disposal facility, wastes are treated as necessary for disposal in a landfill. Treatment is only mandated for mixed wastes, but absorption, size reduction, and compaction may also be done for nonhazardous LLW, depending on the waste and the waste acceptance criteria for the facility. Thus, it is difficult to allocate particular costs to before or after transportation. Table G3-1 includes estimated values for characterization and packaging, and treatment. These costs can be allocated as necessary, depending on how the operations are modeled.

G3-6.2   CFTC LLW Treatment Estimates

The CFTC FOEAS estimated the TPC and LCC costs for a treatment and packaging of LLW expected to be generated by an integrated reprocessing center. Waste volumes were generated based on a task analysis using current work practices (to minimize the volume generated) and treatment practices (such as compaction) to minimize the volume disposed.

Table G3-2 provides the resulting unit cost on a basis of $/m^3 of LLW waste and $/MT of SNF being reprocessed. The later value must be added (including others such as HLW packaging and treatment and uranium solidification and packaging) to the unit cost of reprocessing to obtain a comparable number to those often sited in the literature and other studies for the total unit cost of reprocessing.

The unit costs in Table G3-2 are consistent with those values reported by Yuracko for pre-disposal operator costs. The LCC cost for solid LLW treatment and packaging is equal for either the aqueous reprocess or electrochemical reprocessing waste. However, the unit cost for the electrochemical waste are nearly 3 times the aqueous reprocessing waste reflecting the increase in unit cost based on the lower waste generation from a plant with 40% of the processing capacity.

Table G3-2. CFTC Cost Estimate for Solid LLW Treatment and packaging.

Millions of 2007 Dollars	Benchmark 2 800 MT/yr UREX+1		Benchmark 3 300 MT/yr Electrochemical	
Annual Operations Cost (Nominal Year)	Low	High	Low	High
Labor	15	22	15	22
Utilities	1	2	2	3
Materials	2	3	1	2
Misc. Contracts	0	0	0	1
Misc. Projects	1	2	1	1
Total Annual Operations Cost	20	29	20	29
40 Year LCC				
Labor	761	1142	753	1130
Materials	81	122	85	128
Utilities	74	111	110	164
Contracts	14	21	15	22
Misc. Projects	41	62	42	62
Subtotal: 40-Year Operations	972	1,458	1,005	1,507
Future Capital Projects	0	0	0	0
D&D	1	1	1	1
Subtotal LCC O&M & D&D	972	1,459	1,005	1,508
Early Life Cycle	0	0	0	0
TPC	5	6	5	7
Total LCC	978	1,465	1,011	1,515
Unit LCC Cost ($/m^3)	980	1,469	2,828	4,236
LCC Unit Cost ($/MT SNF)	31	46	84	126
Values may not add due to rounding				

G3-7.   DATA LIMITATIONS

Cost data shown represent 2005 (or in the FOEAS case 2007) dollar unit costs for typical waste characterization, packaging, and treatment. These numbers are subject to change at any time, and can be significantly impacted by specific combinations of contaminants and radionuclides.

G3-8.   COST SUMMARIES

In general, whether the operations are done by the generator or the treatment, storage, and disposal facility, the costs for characterization, packaging and treatment for LLW debris are estimated at approximately $1500/m^3 and liquids at $11,000/m^3. Most commercial nuclear facilities have essentially eliminated MLLW, but debris is estimated at $9,000/m^3 and liquids at $28,000/m^3. Special case waste streams, such as ion-exchange resins, should be estimated at $90,000/m^3.

The module cost information is summarized in the WIT cost summary in Table G3-3. 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 G3-3. Cost summary 'What-It-Takes' (WIT)table for LLW conditioning selected values.

Reference Cost(s) Based on Reference Capacity	Low Cost	Mode Cost	Mean Cost	High Cost
	Based on 800MT/yr Aqueous Process	Based on 800MT/yr High Range		Based on 300MT/yr E-chem Process
LLW Debris				
2012 value	$1,050/m^3	$1,580/m^3	$2350/m3	$4,410/m^3
Escalated to 2020 $ **(G3-1)**	$1,100/m^3	$1,600/m^3	$2,400/m^3	$4,600/m^3
LLW Liquid				
$11,000/m^3 LLW Liquid (2006$)	$3,300/m^3	$11,000/m^3		$22,000/m^3
Escalated to 2020$ **(G3-2)**	$4,200/m^3	$13,800/m^3	$15,200/m^3	$27,700/m^3
Resins				
$90,000/m^3 Resins (2006$)	$81,000/m^3	$90,000/m^3		$99,000/m^3
Escalated to 2020$ **(G3-3)**	$101,900/m^3	$113,300/m^3	$113,300/m^3	$124,600/m^3

Cost data has been rounded to two or three significant digits. Values are sensitive to market, specific waste characteristics, and regulatory changes. Waste disposal at EnergySolutions has been essentially monopolistic, but waste control specialists are still trying to establish themselves as a fully permitted facility. Similarly, waste disposal at Hanford and Barnwell has been limited to regional state pacts, but the National Test Site now accepts wastes, and the equilibrium on costs is expected to change. Costs for LLW/MLLW are +100%, -30%, based on experience of the author and recognition of the wide range over which the market may evolve. The triangular distributions based on the costs in the WIT table are shown in Figures G3-6, G3-7, and G3-8
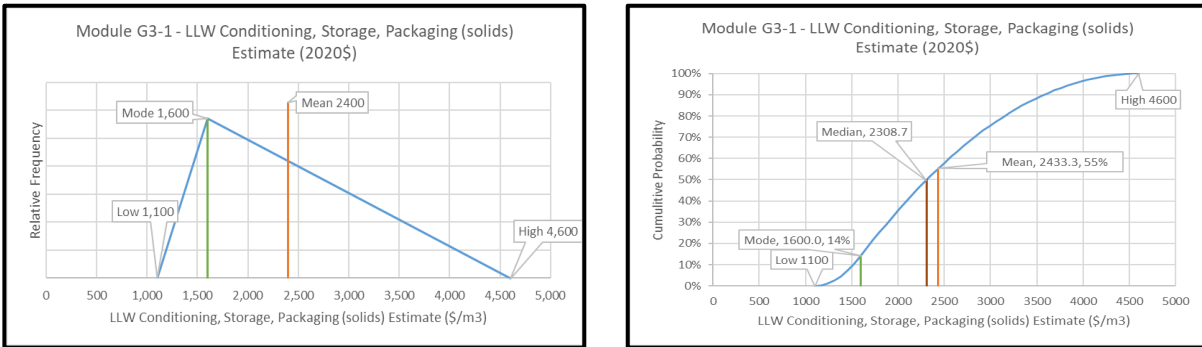
Figure G3-6. Module G3-D LLW conditioning estimated cost frequency and cumulative distributions.
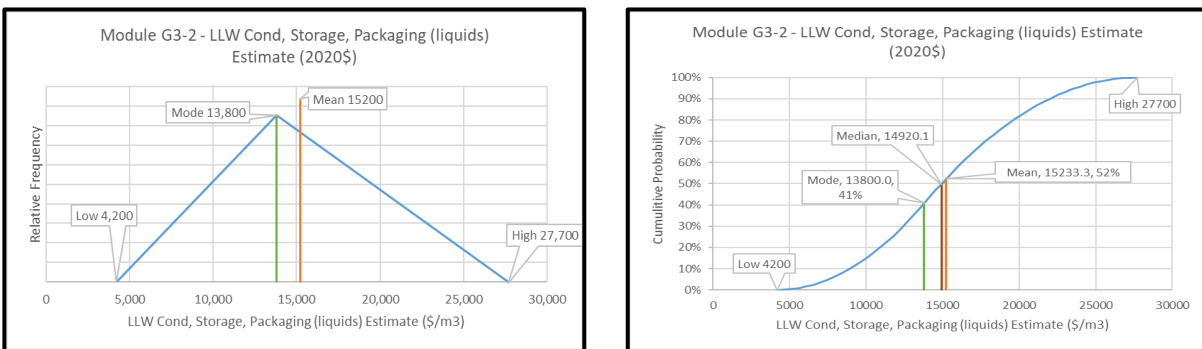
Figure G3-7. Module G3-L LLW conditioning estimated cost frequency and cumulative distributions.
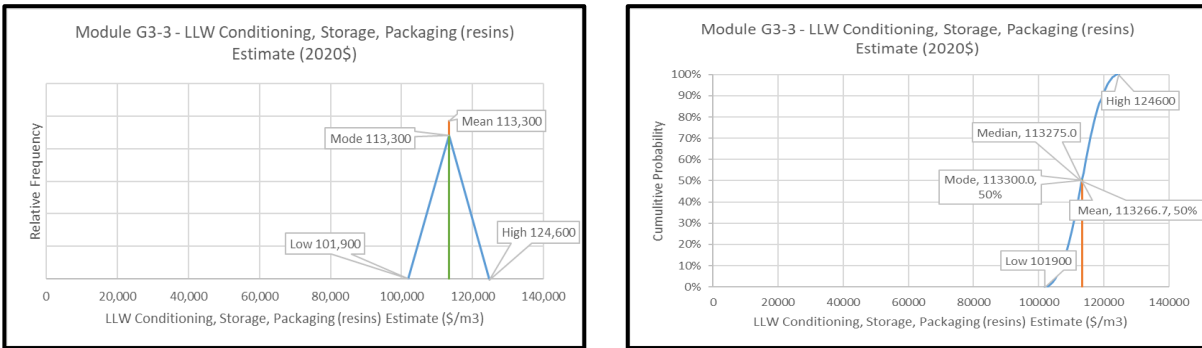
Figure G3-8. Module G3-Resin LLW conditioning estimated cost frequency and cumulative distributions.

G3-9.   SENSITIVITY AND UNCERTAINTY ANALYSES

None available.

G3-10.   REFERENCES

See G5-10 and G5-11.

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Module G4

GTCC Process Waste Conditioning, Storage, and Packaging

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G4 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2006	All	Version of AFC-CBR in which Module first appeared: First became separate submodule in 2006.
	2009	All	Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges: 2009 for all GTCC fission product classes.
			New technical/cost data which has recently become available and will benefit next revision: None identified.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module G4
GTCC Process Waste Conditioning, Storage, and Packaging

G4-MD.   SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**

- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only from last time values underwent technical assessment: 2009

- **Estimating Methodology for latest technical updates (2009) from which this 2017 update was escalated:** Data from bottom-up estimates generated for hypothetical Consolidated Fuel Treatment Center (CFTC) and subsequent Engineering Alternative Studies for other type reprocessing plant studies performed under GNEP. Many separated fission products would be treated as GTCC.

G4-1.   BASIC INFORMATION

All of the process waste generated by reprocessing would be currently classified as high-level waste (HLW) except for the compacted hulls and hardware. Waste from the captured and treated volatile radionuclides (C-14, I-129, Kr-85, and H-3) and solidified and packaged Cs/Sr can potentially be reclassified as Greater-than-Class-C (GTCC) (or even low-level waste [LLW]) waste. Module G-1 includes the cost of solidifying and packaging the Cs/Sr using a number of different processes and will not be repeated in this module since the cost of treatment is the same regardless of the waste classification. The disposal cost may vary under differing waste classification assumptions.

This module is dedicated to those wastes that contain sufficient long or short-lived radionuclides to be classified GTCC and are:

"Waste that is not generally acceptable for near-surface disposal is waste for which form and disposal methods must be different, and in general more stringent, than those specified for Class C waste. In the absence of specific requirements in this part, such waste must be disposed of in a geologic repository as defined in part 60 or 63 of this chapter unless proposals for disposal of such waste in a disposal site licensed pursuant to this part are approved by the Commission." (40 CFR 61)

G4-2.   FUNCTIONAL AND OPERATIONAL DESCRIPTION

GTCC wastes may require specialized containment/shielding/waste forms/storage canisters/storage that may be a hybrid of low-level, transuranic, and HLW, depending on the alpha or beta/gamma radiation prevalence. In general, the beta/gamma radiation from these wastes will require some shielding or special handling that may not be necessary for Class A/B/C wastes. Also, depending on the nature of the waste matrix and the treatment technology, wastes that are not transuranic (TRU) (>100 nCi/g), but that contain appreciable TRU contamination, may also require alpha containment similar to TRU wastes. Refer to LLW and TRU waste modules for more detail.

G4-3. PICTURES AND DIAGRAMS

These wastes may require packaging and handling similar to HLW, such as prepared in the Defense Waste Processing Facility (DWPF) in Figure G4-1.

Figure G1-1. Defense waste processing plant at the Savannah River Site.

G4-4. MODULE INTERFACES

Module G4 receives GTCC wastes from reprocessing, including all streams not regulated as HLW, containing <100 nCi/g TRU, and exceeding the limits established in 10 CFR 61 for Classes A, B, or C LLW. Wastes exit potentially to Near Surface Disposal (Module J) if considered LLW, Geologic Repository (Module L2) if treated as HLW/TRU, or Alternative Disposal Concepts (Module M).

In terms of the fuel processing flowsheets under development and the new streams to be produced such as the iodine, cesium/strontium, tritium, and technetium wastes, any of these could be considered GTCC if not regulated as HLW and more concentrated than the limits defined in 10 CFR 60.

As stated above, all streams from processing used fuel could be potentially classified as HLW (except for the hulls and hardware) under current regulations. In the United States, this is a functional rather than characteristic designation. Also in the United States, defense wastes that are not HLW that contain ≥100 nCi/g TRU are "TRU wastes," and the WIPP repository for these wastes is restricted to receiving waste derived from defense materials. Commercial wastes other than HLW are designated LLW, and the numerical limits designating disposition requirements for Classes A, B, and C, and GTCC are defined in 10 CFR 61 and described in detail in Submodule G3 on LLW. Though these wastes are relatively well-defined based on characteristics, the disposition pathway for GTCC waste, a geologic repository, has not yet been designed or designated. Thus, for the purposes of this report, it is assumed that the regulations will be reevaluated and changes will allow some of the disposition options shown in Table G1-1. In summary, these changes may include consideration of the concept of "decay storage": secure storage facilities to allow problematic radionuclides such as cesium, strontium, tritium, and noble gases to decay to LLW limits. These materials must be stored for several hundred years isolated from the biosphere and protected against unregulated use.

G4-5.   SCALING CONSIDERATIONS

These facilities are unique and designs are not readily extrapolated. It is not expected that future facilities will emulate current facilities and unit costs may be significantly different. Therefore, scaling is not considered practical.

G4-6.   COST BASES, ASSUMPTIONS, AND DATA SOURCES

Costs for G4 modules were further detailed in order to support current assumptions on the aqueous and EChem separated HLW streams, waste forms, and waste loading. These wastes consist of gases (H3, Kr, Xe), metals (ZrSS) and Iodine. Costs were developed for each type of waste.

Gas wastes: Modules G4-1A (Aqueous) and G4-1E (EChem) provide waste conditioning for the gaseous wastes (H3, Kr, Xe). Cost basis was derived from study on Krypton encapsulation preconceptual design (Knecht 1994). Off-gas conditioning costs range from $8,000/m^3 gas to $15,000/m^3 gas, with a nominal cost of $11,200/m^3 gas. Aqueous and EChem off gases are conditioned and packaged then placed in long-term managed decay storage.

The Knecht study was based on 233 m^3/yr of off-gas (99% krypton) produced from a 2,000 MTHM/yr reprocessing plant. This rate corresponds to 873 kg Kr/yr for the zeolite encapsulation part of the reprocessing complex. Table 7-7 from the Knecht report gives a discounted life cycle cost of $21.9M in 1994 dollars or $32.4M if converted to today's dollars. Since unit costs ($/unit) can be calculated by dividing discounted life cycle costs by discounted annual production, the discounted production of 233 m^3 gas per year for 30 years at a 7% discount rate gives an overall discounted production of 2891 m^3. Dividing $32.4M by 2891 gives a unit cost of $11,200/m^3 of off-gas. This was designated as the nominal value. The high and low values were selected to give approximately a plus or minus 30% variation from the nominal value.

The CFTC EAS included cost estimates for similar volatile off-gas capture (H-3 capture and grouting, C-14 capture as carbonate and grouting, cryogenic capture and separation of Kr, iodine adsorption on mordenite and grouting), compaction of Zr hulls and stainless steel hardware. All these operations were to be conducted in the fuels receipt and dissolution building and are therefore inherently included in the cost of reprocessing (see module F1).

The CFTC FOEAS did examine the cost of eliminating the Kr-85 and C-14 capture and treatment and determined the TPC cost ranged from $112M to $156M.

Iodine. Module G4-4A (Aqueous derived) conditions iodine for placement in GTCC intermediate depth disposal. The nominal cost of $67,000/m^3 iodine is based on an engineering estimate of $25M capital and $2M/year O&M for a 50 m^3/year iodine throughput. The costs range from $50,000/m^3 to $80,000/m^3 iodine.

Zr/SS. Module G4-5A (Aqueous) is estimated the same as G1-2E (EChem metal alloy conditioning of ZrSS). This waste is dispositioned to GTCC intermediate depth disposal.

G4-7.   DATA LIMITATIONS

Advanced commercial fuel processing flowsheets that generate waste streams such as concentrated cesium and strontium, iodine, and technetium streams for which disposal options are not currently specified and glass may be inappropriate.

G4-8.   COST SUMMARIES

GTCC may be remote handled and generally not allowed in commercial surface landfills, but this has occurred on DOE reservations. Premium charges based on curie content of specific radionuclides are extremely variable due to the limited capacity for these materials per disposal site permits. Developing a repository specifically for GTCC wastes or codisposal with TRU waste is an unknown at this time.

The module cost information is summarized in the WIT cost summary in Table G4-2. 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).

The cost estimates in Table G4-2 apply to GTCC derived from both aqueous and Echem reprocessing activities.

Table G4-2. Cost summary 'What-It-Takes' (WIT)table for GTCC waste conditioning selected values.

Reference Cost(s) Based on Reference Capacity	Low Cost	Mode Cost	Mean Cost	High Cost
LLW-GTCC Off-gas Absorber (H3, Kr, Xe) [2009$]	$8,000/m^3 gas	$11,200/m^3 gas		$15,000/m^3 gas
Escalated to 2020 $ [19 % increase from 2009] **(G4-1A; G4-1E)**	$9,500/m^3 gas	$13,400/m^3 gas	$13,600/m^3 gas	$17,900/m^3 gas

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.

The triangular distribution based on the costs in the WIT Table is shown in Figure G4-2 (same for both aqueous and E-chem absorber off gases.)
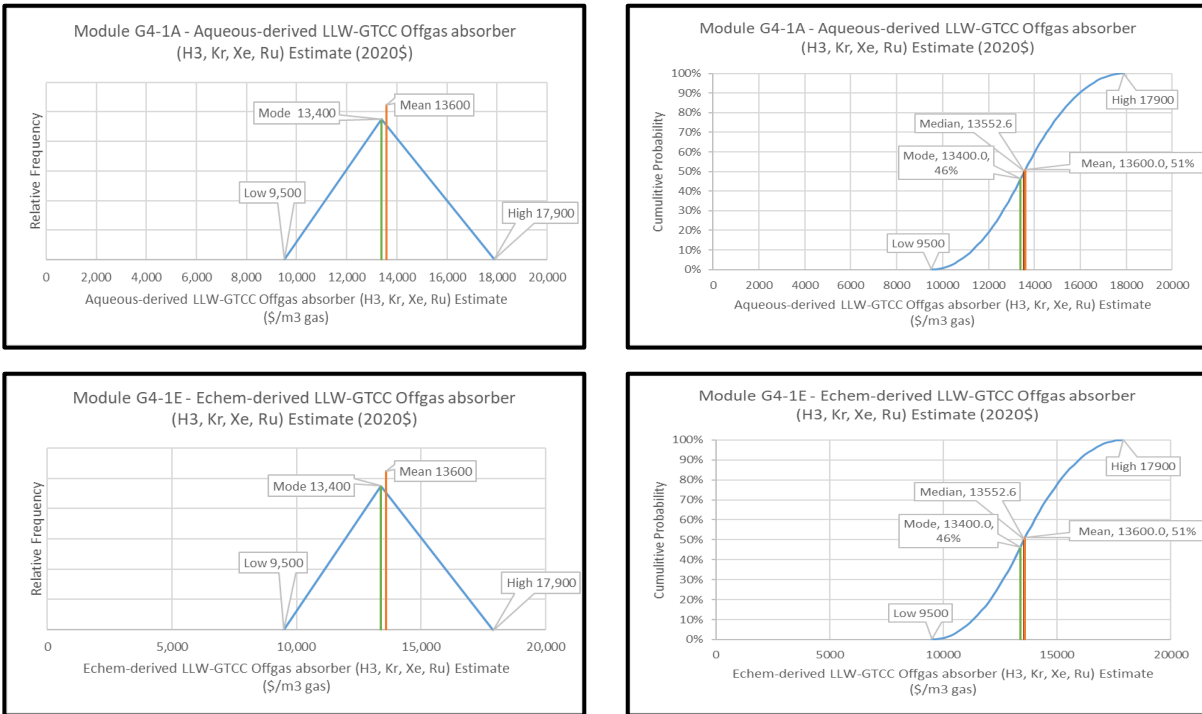
Figure G4-2. Module G4-1Aqueous and E-Chem offgas absorber.

G4-9. SENSITIVITY AND UNCERTAINTY ANALYSES

None available.

G4-10. REFERENCES

See G5-10 and G5-11.

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Module G5

GTCC Secondary Waste Conditioning, Storage, and Packaging

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G5 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2006	All	Version of AFC-CBR in which Module first appeared: First became separate submodule in 2006.
	2009	All	Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges: 2009
			New technical/cost data which has recently become available and will benefit next revision: New data on waste preparation costs for WIPP might be available. WIPP recently reopened, and DOE sites are shipping permanent packages for geologic emplacement.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module G5
GTCC Secondary Waste Conditioning, Storage, and Packaging

G5-MD.   SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**

- Nature of this FY21 Module update from previous AFC-CBRs: Escalation only from last time values underwent technical assessment: 2009

- Estimating Methodology for latest technical updates (2009) from which this 2017 update was escalated: Data from bottom-up estimates generated for hypothetical Consolidated Fuel Treatment Center (CFTC) and subsequent Engineering Alternative Studies for other type reprocessing plant studies performed under GNEP. Some data are based on USDOE estimates for preparing wastes for emplacement in WIPP (Waste Isolation Pilot Plant)

G5-1.   BASIC INFORMATION

Future fuel cycles are planned to include transuranic (TRU) recovery for recycle as fuel for fast reactors to destroy TRU and to generate additional energy. Goals for recovery of TRU are very aggressive with an overall recovery of approximately 99.9%. This includes leaching and rework of off-specification products, scraps, and process residuals to further reduce losses. Keeping losses less than 0.1% could allow expanding the capacity of a geologic repository for high-level waste (HLW) by two orders-of-magnitude. However, there will still be losses that contaminate consumable items and equipment, and some of these wastes will likely be classified as Greater-than-Class-C (GTCC) low-level waste (LLW) containing TRU contamination.

GTCC waste is defined as:

> "Waste that is not generally acceptable for near-surface disposal is waste for which form and disposal methods must be different, and in general more stringent, than those specified for Class C waste. In the absence of specific requirements in this part, such waste must be disposed of in a geologic repository as defined in part 60 or 63 of this chapter unless proposals for disposal of such waste in a disposal site licensed pursuant to this part are approved by the Commission." (40 CFR 61)

In general, however, these wastes will be disposed of in a geologic repository. The similarities of commercial GTCC and defense TRU waste allow direct comparison of the treatment and disposal concepts (e.g. Waste Isolation Pilot Plant [WIPP] in the U.S.).

This module includes waste conditioning, certification, interim storage, and packaging of GTCC secondary generated from reprocessing spent nuclear fuel (SNF) using either aqueous or electrochemical processing. The closest analogues are the activities underway at several Department of Energy (DOE) sites that are shipping TRU waste to WIPP. Assuming that a future TRU waste repository would be similar to WIPP in design and operation, the costs can be estimated from current activities.

G5-2.   FUNCTIONAL AND OPERATIONAL DESCRIPTION

The GTCC Conditioning, Storage, and Packaging Facility will likely be a part of future nuclear facilities, but may also be operated similar to LLW disposal operation in which the treatment process is contiguous with the disposal such as the case with EnergySolutions, or may be a separate contracted facility such as the Duratek facility in Tennessee; Pacific EcoSolutions Inc., (PEcoS) in Washington; or Permafix headquartered in Florida that all ship the conditioned wastes for disposal such as Barnwell in South Carolina or EnergySolutions. External facilities must be capable of receiving wastes by truck and rail and must have sufficient analytical facilities or access to such facilities to ensure that the materials they receive are within the limits imposed by their permits. At a minimum, the facilities must be able to inspect and repackage to meet the waste acceptance criteria for the landfill. Other conditioning and treatment services offered will likely be based on return on investment and local expertise. Some of the more common services include:

- Supercompaction to reduce volume of compressible materials

- Size reduction to reduce volume of oversized materials such as construction debris

- Stabilization using sorbents to immobilize free liquids

- Stabilization using a cement and/or a pozzolonic material to reduce leachability of metals

- Macroencapsulation of debris including lead bricks

- Chemical oxidation for reactive metals and some organics

- Thermal desorption to separate organic constituents from waste matrices

- Incineration to minimize ultimate volume of combustibles or destroy solvents and other organic materials

- Specialized treatability studies and treatment for unique wastes.

Disposal criteria are likely to be similar to WIPP. WIPP waste acceptance criteria does not allow receipt of:

- Free liquids in excess of 1% of the container volume or 1 inch, whichever is less

- Sealed containers over 4 L

- Electrochemical radioactive materials over 1% by weight

- Ignitable, corrosive, or reactive wastes according to 40 CFR 261

- Explosives, corrosives, or compressed gases

- Flammable headspace gases >500 ppm.

Though this module does not include the repository itself (Module L), these requirements do imply the characterization capabilities to identify any of these characteristics and rectify them if found. Thus, some combination of verifiable information on how the waste was generated and analytical techniques for all these characteristics must be available.

Costs have been gathered and reported by the National Energy Technology Laboratory (NETL) (GAO 2000) including the following:

- Compilation of acceptable knowledge on the history of the waste

- Nondestructive assay

- Radiography and visual examination

- Gas generation testing

- Head space gas sampling and analysis.

At a minimum, it is likely that drums of TRU waste generated in the future will be subject to manual sorting and packaging and possibly radiography to verify packaging records. In the event that there are discrepancies identified, sampling and analytical capabilities designed for alpha containment and/or manual resorting and repackaging will be needed.

In addition to packaging waste drums and boxes to meet the waste acceptance criteria, receipt, inspection, decontamination, loading, and shipping of casks will also be necessary.

G5-3. PICTURES AND DIAGRAMS

Future generation of GTCC wastes will probably be better characterized than legacy wastes, because disposal in a repository will likely be planned, rather than assuming the waste can be buried in a surface landfill, as was the practice prior to 1970. Future wastes will probably be primarily stabilized waste forms, including ion-exchange media and precipitates encapsulated/mixed in a relatively inert matrix. Some wastes may still be generated that are debris. Figure G5-1 shows examples of legacy waste packaging that will hopefully serve as examples of what should be avoided.

Figure G5-1. Legacy TRU wastes packaged in 55-gallon drums with and without liners, bags, and stabilizing sorbent media.

Much has been learned from expensive retrieval and characterization activities for legacy wastes, and it is likely that future waste disposal will be more streamlined and cost effective. Figures G5-2 and G5-3 are photographs from Idaho National Laboratory (INL) showing waste drum tomographic and headspace sampling equipment. Figure G5-4 is a collage of pictures from a Sandia Web site showing one potential design for a manual GTCC waste sorting system. Handling and sampling GTCC wastes is very expensive,

and hopefully better record keeping will allow handling these materials one time in the future to stabilize and prepare them for disposal.

Figure G5-5 shows a cutaway of the TRUPACT-II cask that is used for overland transport of packaged TRU wastes. Note the sophisticated design of the cask to ensure containment of the wastes even in the event of foreseeable accident scenarios. Figure G5-6 shows a typical truck shipment of three casks, each capable of holding 14 drums of waste.

Figure G5-2. X-ray tomographic equipment for imaging drummed waste without opening the drum.

Figure G5-3. Headspace gas sampling of heated drum using Fourier transform infrared.
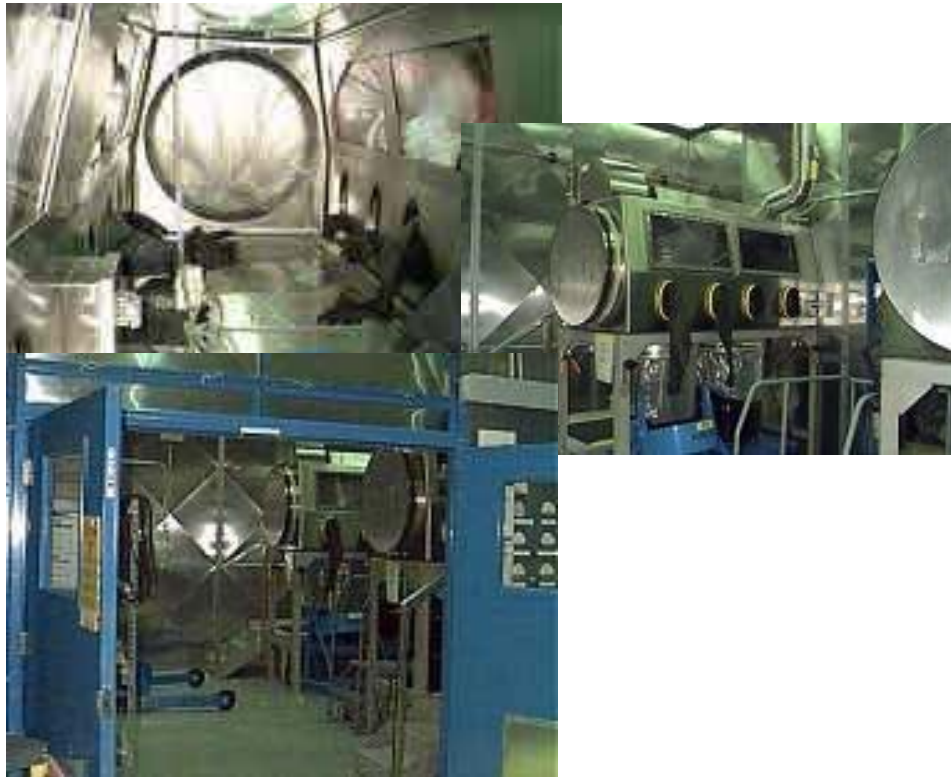

Figure G5-4. Collage of pictures showing a TRU waste sorting system.
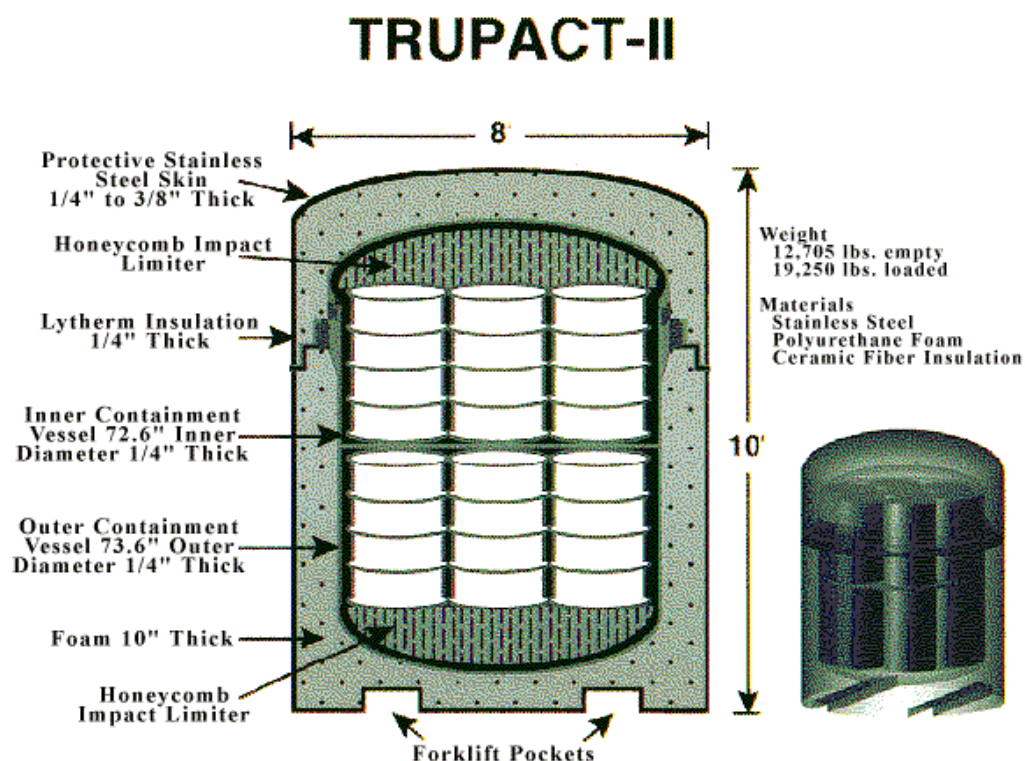
Figure G5-5. Schematic of TRUPACT-II shipping cask for TRU wastes.

Figure G5-6. Truck shipment of three TRUPACT-II casks.

G5-4.   MODULE INTERFACES

Module G5 includes waste conditioning, certification, and interim storage of GTCC secondary wastes that include TRU. These wastes could be shipped (Module O1) to a Geologic Repository (Module L) or an Other Disposal Concept (Module M) that is yet to be determined. Most TRU wastes are expected to come from Modules F1, D1-2, D1-4, D1-5 and combined Modules F2/D2, the fuel separations modules. In fuel fabrication, there is expected to be a significant effort made to leach or reprocess off-specification materials to recover TRU. Materials may also be recycled to separations to purify TRU. However, it is still expected that in addition to consumables such as protective clothing, filters, and analytical solutions,

there will also be contaminated equipment such as gloveboxes, grinding machines, and molds that may contain over 100 nCi/g TRU.

G5-5.   SCALING CONSIDERATIONS

This module does not represent a "facility" and cannot be scaled as such.

G5-6.   COST BASES, ASSUMPTIONS, AND DATA SOURCES

G5-6.1 Defense TRU Waste Analogies

The closest analogous costs are remote-handled TRU (RH-TRU). Costs are derived from estimates made for WIPP. The information is from a study of TRU waste characterization and certification costs conducted by the NETL for WIPP (GAO 2000). The study was based on a combination of actual 2002 costs from INL and Rocky Flats Environmental Technology Site, and on estimated 2003 costs from Savannah River Site. Capital costs were not included.

Based on a typical drum of contact-handled TRU waste, the average life-cycle cost of characterization is $3,850 per drum (in 2002 dollars). Using 208 L per drum, this translates to $18,500/m^3.

These costs were developed based on the sum of the average cost for a set of 15 individual waste certification activities (e.g., real-time radiography, nondestructive assay, and head space gas sampling). Furthermore, the data were based on the certification of 17,900 drums from a stored waste population of 24,600 drums, plus the visual examination of 14,200 drums. The cost of each activity was prorated by the percentage of drums for which the activity was applicable.

Table G5-1 shows the cost of three particularly high-cost activities to illustrate how dependent the cost of characterization is on specific activities. For example, if the waste requires solids coring and sampling, then the total cost of certification would jump to about $115,000/m^3 (2001 dollars). To bring the cost back down to the average, solids coring and sampling would have to be restricted to approximately 1% of the waste drums (specific numbers can be obtained from the WIPP TRU characterization cost analysis [GAO 2000]). The actual cost for an individual certification program then depends on the waste type, the certification activities required, and the number of containers available for averaging. The $18,500/m^3 represents a good current estimate for a large number of drums of waste of various types.

Table G5-1. Examples of high-cost characterization activities.

Activity	Average Cost (per drum and m^3)	
	Cost per Drum	Cost/m^3
Visual examination and retrievably store	$22,500	$108,000
Solids coring and sampling (FY 2001)	$24,000	$115,000
Solids analysis (FY 2001)	$63,000	$303,000

The method of computing the values in Table G5-2 is shown below with an example.

Table G5-2. Estimated characterization and certification costs for TRU wastes[a].

Waste Type	Characterization $/m^3
CH-TRU	18,500
a. Costs do not include capital facility costs, waste treatment, or transportation.	

From Table 4.3-1 of the National TRU Waste Management Plan (NTWMP), "Baseline Cost Data," (NETL 2003) the quoted dollar value for INL in Fiscal Year (FY) 2002 was $72,937,000. The DOE Carlsbad Field Office (CBFO) estimates that 75% of this value is used in waste characterization, certification, and preparing waste for shipment. Therefore, INL cost for TRU waste characterization and certification during FY 2002 is shown in Equation (1).

$$\$72,937,000 \times 0.75 = \$54,702,750. \tag{1}$$

The method of estimating the volume characterized and certified is shown below. The number of planned shipments to WIPP is given in Table 3.2.1-1 of the NTWMP; however, the volume of waste is not given. The following conservative assumptions were used to determine a best-case estimate of the volume disposed:

- Each shipment consists of three Transuranic Package Transporter Model-IIs (TRUPACT-II)

- Each TRUPACT-II is full (i.e., 14 drums/TRUPACT-II or 42 drums/shipment)

- Each drum has a volume of 0.208 m^3.

Again, using an FY 2002 INL reported value of 437 shipments and the assumptions above, the volume of waste is as shown in Equation (2).

$$437 \text{ shipments} \times 42 \text{ drums/shipment} \times 0.208 \text{ m}^3/\text{drum} = 3,817 \text{ m}^3. \tag{2}$$

This volume, divided into the cost above, gives the characterization and certification cost of $14,327/m^3.

In most cases, the number of drums shipped is less than 42 because of transportation issues such as weight or wattage. Based on the INL shipping rate during the 3,100 m^3 project, the above estimate gives a volume estimate approximately 25% too high, or a cost estimate 25% too low in FY 2002. As such, the value calculated here should be considered a practical minimum. If the estimate of $14,327/m^3 is increased by 25%, it becomes $17,900/m^3, which is within 3% of the NETL estimate of $18,500/m^3 for characterization and certification of contact-handled TRU. Thus, the same approximate cost can be estimated from two approaches, and this is believed to be a good baseline.

G5-6.2   CFTC GTCC Treatment Estimates

The Consolidated Fuel Treatment Center (CFTC) Follow-on Engineering Alternative Studies (FOEAS) estimated the total project cost (TPC) and life cycle cost (LCC) for a treatment and packaging of GTCC waste expected to be generated by an integrated reprocessing center. Waste volumes were generated based on a task analysis using current work practices (to minimize the volume generated) and treatment practices (such as compaction) to minimize the volume disposed.

Table G5-2 provides the resulting unit cost on a basis of $/m^3 of GTCC waste and $/MT of SNF being reprocessed. The later value must be added (including others such as HLW packaging and treatment and uranium solidification and packaging) to the unit cost of reprocessing to obtain a comparable number to those often sited in the literature and other studies for the total unit cost of reprocessing.

The unit costs in Table G5-2 are consistent with those values reported for defense TRU pre-disposal operator costs. The LCC cost for solid GTCC treatment and packaging is somewhat less electrochemical reprocessing waste than for the aqueous reprocessing waste. However, the unit cost for the electrochemical waste is slightly higher than the aqueous reprocessing waste reflecting the increase in unit cost based on the lower waste generation from a plant with 40% of the processing capacity.

Table G5-2. CFTC cost estimate for solid GTCC treatment and packaging.

Millions of 2007 Dollars	Benchmark 2 800 MT/yr UREX+1		Benchmark 3 300 MT/yr Electrochemical	
Annual Operations Cost (Nominal Year)	Low	High	Low	High
Labor	15	23	12	18
Utilities	1	2	2	2
Materials	2	3	1	2
Misc. Contracts	0	0	0	1
Misc. Projects	1	2	1	1
Total Annual Operations Cost	**20**	**29**	**16**	**24**
40 Year LCC				
Labor	769	1154	619	928
Materials	82	123	70	105
Utilities	75	112	90	135
Contracts	14	21	12	18
Misc. Projects	42	62	34	51
Subtotal: 40-Year Operations	**982**	**1,473**	**825**	**1,238**
Future Capital Projects	0	0	0	0
D&D	4	5	2	3
Subtotal LCC O&M & D&D	**986**	**1,478**	**828**	**1,241**
Early Life Cycle	0	1	1	1
TPC	31	43	16	23
Total LCC	**1,017**	**1,522**	**845**	**1,265**
TPC Unit Cost, 40 yr amortization ($/m^3)	**758**	**1,052**	**554**	**766**
Unit LCC Cost ($/m^3)	**25,047**	**37,480**	**28,615**	**42,849**
LCC Unit Cost ($/MT SNF)	**32**	**48**	**70**	**105**
Values may not add due to rounding. 0% discount rate				

G5-7.   DATA LIMITATIONS

The quoted values from defense TRU operations are baseline estimates based on operational costs; they do not include capital costs for the equipment or facilities used for characterization and certification. Characterization and certification costs can be dominated by sampling and analysis, which can be from 6 to 30 times the average cost of characterization and certification. Characterization costs reported here should be considered bounding. Much of the characterization is necessitated by a lack of acceptable knowledge due to the poor data quality describing legacy wastes. In the future, it is expected that TRU wastes generated by commercial facilities and future reprocessing will be well characterized, and most characterization will not be necessary. Also, a significant fraction of the characterization cost is related to container handling between characterization activities, and this should be greatly reduced for future wastes.

However, the CFTC studies made similar assumptions as regards the reduced characterization requirements for non-legacy waste and obtained somewhat higher unit costs including capital.

Costs for RH-TRU were not estimated separately from contact-handled TRU costs in the defense waste report. Costs estimated based on the NTWMP are simple averages; therefore, the costs are reasonably applicable to contact-handled TRU waste because the current plan is to fill WIPP repository

with 95% contact-handled TRU waste. If waste characterization and treatment must be done remotely, the costs could be 3 to 10 times greater.

The CFTC study captures the cost of remote handled GTCC (expected to be the activated hulls and hardware, which have a high Co-60 neutron source) packaging in the reprocessing module since this operation is conducted inside the Fuel Receipt and Dissolution Building. The costs reported here are for the contact-handled GTCC waste only.

G5-8.   COST SUMMARIES

The module cost information is summarized in the WIT cost summary in Table G5-3. 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.

Costs for TRU wastes are driven almost entirely by regulations. If it can be assumed that future commercial wastes will be produced by well-characterized processes, characterization costs will diminish, and treatment costs should be minimal and will be covered under operation of the recycling/separations facility.

The triangular distribution based on the costs in the WIT Table is shown in Figures G5-7. The distribution is skewed toward the low cost (the nominal was selected to be the low cost) because it is based on experience from WIPP. The distributions for RH-TRU are judged to be skewed toward low cost, but have potential to increase due to potential regulation of commercial facilities.

Table G5-3. Cost summary 'What-It-Takes' table for GTCC secondary waste conditioning.

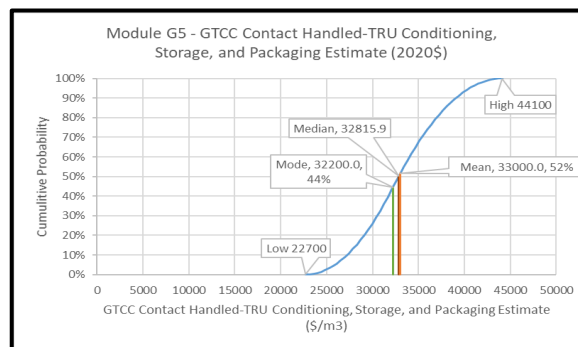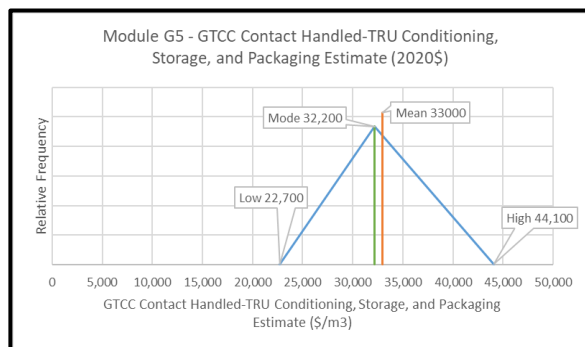| Reference Cost(s) Based on Reference Capacity	Low Cost	Mode Cost	Mean Cost	High Cost
2009$ >>>	$19,000/m³ GTCC	$27,000/m³ GTCC		$37,000/m³ GTCC
Escalated to 2020 $ **(G5)**	$22,700/m³	$32,200/m3	$33,000/m³	$44,100/m³
	Average of Defense TRU waste processing from INL actual costs	Average of the high and low		CFTC EAS high range for 800MT/yr aqueous reprocessing

Figure G5-7. Module G5 GTCC secondary waste conditioning estimated cost frequency distribution.

G5-9.   SENSITIVITY AND UNCERTAINTY ANALYSES

None available.

G5-10. MODULE G REFERENCES

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