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Follow-on Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation

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EXECUTIVE SUMMARY

The Hanford Site, in southeast Washington State, is preparing to disposition approximately 56,000,000 gallons (56 Mgal) of radioactive and chemically hazardous wastes currently stored in underground tanks at the site. Tank wastes will be divided into a high-activity fraction and a low-activity fraction for subsequent treatment and disposition. A waste processing and treatment facility, the Waste Treatment and Immobilization Plant (WTP), will include the high-level waste (HLW) vitrification facility (WTP HLW Vitrification Facility) for immobilizing the high-activity fraction and a low-activity waste (LAW) vitrification facility (WTP LAW Vitrification Facility) for immobilizing the low-activity fraction. Both facilities will use vitrification technology to immobilize the Hanford tank wastes in a glass waste form.

The volume of LAW to be treated and disposed of following waste retrieval and WTP operations will exceed the planned processing capacity of the WTP LAW Vitrification Facility. ORP-11242, *River Protection Project System Plan*,[1] estimates a shortfall in LAW treatment capacity of approximately 56 Mgal, approximately 50% of the projected LAW volume.[2] To maintain the planned tank waste processing mission schedule, the U.S. Department of Energy (DOE) will require additional LAW treatment capacity (termed "supplemental LAW") external to the WTP process. LAW must be solidified by a treatment technology before the waste can be permanently disposed of in an approved DOE on-site disposal facility or a commercial (state or U.S. Nuclear Regulatory Commission [NRC]-licensed) off-site mixed low-level waste disposal facility. A decision on the approach to supplemental LAW treatment, processing, and disposal has not yet been made.

Section 3125 of the Fiscal Year 2021 National Defense Authorization Act (NDAA21),[3] directs DOE to enter into an arrangement with a Federally Funded Research and Development Center (FFRDC) to conduct an analysis that:

> *"…shall be designed, to the greatest extent possible, to provide decisionmakers with the ability to make a direct comparison between approaches for the supplemental treatment of low-activity waste at the Hanford Nuclear Reservation based on criteria that are relevant to decision making and most clearly differentiate between approaches."*

In accordance with Section 3125, this analysis provides an assessment of the following:

- The most effective potential technology for supplemental treatment of LAW that will produce an effective waste form
- The differences among approaches for the supplemental treatment of LAW considered as of the date of the analysis
- The compliance of such approaches with the technical standards described in Section 3134 of the NDAA for Fiscal Year 2017 (NDAA17)[4]
- The differences among potential disposal sites for the waste form produced through such treatment, including mitigation of radionuclides, including technetium-99 (^{99}Tc), selenium-79 (^{79}Se), and iodine-129 (^{129}I), on a system level

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[1] ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

[2] The volume of waste to be treated is much greater than the volume currently in the waste tanks because water is added during retrieval, staging, and pretreatment processes.

[3] *National Defense Authorization Act for Fiscal Year 2021*, Public Law 116–283, January 1, 2021.

[4] *National Defense Authorization Act for Fiscal Year 2017*, Public Law 114–328, December 23, 2016.

- Potential modifications to the design of facilities to enhance performance with respect to disposal of the waste form to account for: (1) regulatory compliance, (2) public acceptance, (3) cost, (4) safety, (5) expected radiation dose to maximally exposed individuals over time, and (6) differences among disposal environments
- Approximately how much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals to reduce disposal costs for radionuclides
- Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level by the performance assessment of a potential disposal site and, if the radionuclides cannot be left in the waste form, how to account for the secondary waste stream
- Other relevant factors relating to the technology, including: (1) costs and risks in delays with respect to tank performance over time, (2) consideration of experience with treatment methods at other sites and commercial facilities, and (3) outcomes of the DOE Office of Environmental Management Test Bed Initiative at Hanford.

In addition to consideration of vitrification and fluidized bed steam reforming technologies, Section 3125 of NDAA21 requires the FFRDC team to perform additional analysis of grout treatment options building on the analysis in the FFRDC report for Section 3134 of NDAA17. Because this is a follow-on analysis, some of the summary and overview information presented is repeated from the NDAA17 analysis.

The focus of the FFRDC analysis is on technologies and approaches, and the FFRDC team is made up of technical experts in appropriate disciplines from the national laboratories, academia, industry, and private institutions. The NDAA21 also requires a concurrent review of the analysis by a committee of technical experts selected by the National Academies of Science, Engineering, and Medicine.

The FFRDC team concluded that vitrification and grouting technologies are technically viable for supplemental treatment of LAW. These approaches do not pose high technical risks and there is high confidence that any unforeseen technical issues can be resolved. In contrast, fluidized bed steam reforming (FBSR) implementation at Hanford, while viable, would be a first-of-a-kind technology implementation, with the potential for substantial technical challenges.

The FFRDC team found significant differences among alternatives in cost, duration, and likelihood of successful project completion. The annual and total cost to implement capital projects for some of the proposed alternatives is significantly greater than for others. Additionally, based on benchmark budget scenarios, non-grout technologies pose a significant risk of extended processing durations that would increase the risk of further deterioration of the waste storage tanks prior to waste retrieval/processing. Only alternatives employing grout technology appear to be technically viable, low-to-moderate risk, and flexible enough to implement under a range of constrained budget scenarios without significant impact to the WTP HLW Vitrification Facility mission completion schedule. Alternatives with off-site immobilization and disposal offer additional advantages due to their ability to begin processing much sooner. This finding is robust under the full range of sensitivity analyses performed by the FFRDC team.

The FFRDC team makes the following recommendation:

DOE should expeditiously secure and implement multiple pathways for off-site grout solidification/ immobilization and disposal of LAW in parallel with the direct-feed low-activity waste (DFLAW) vitrification process.

This recommendation is based on a comprehensive evaluation of multiple alternatives considering (1) long-term effectiveness (environmental and safety risk after disposal), (2) implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration), (3) likelihood of successful mission completion (including technical, engineering, and resource-related risks), and (4) lifecycle costs (discounted present value). The intent of multiple pathways is to provide parallel contractual agreements with multiple facilities for off-site solidification/immobilization and disposal to minimize risks associated with potential facility- or state-specific implementation challenges.

The recommended approach can be beneficial in many ways, as the approach:

- Provides the capability to achieve the most rapid reduction in the amount of waste stored in the Hanford single-shell tanks and double-shell tanks by using available off-site solidification/ immobilization and disposal capacity, and therefore results in the most rapid reduction in risk to human health and the environment attributed to potential future unplanned tank waste releases.
- Provides additional long-term environmental protection, including to the aquifers underlying the Hanford Site and the Columbia River, by disposing of a significant portion of the inventory of risk-driving constituents (e.g., ^{99}Tc, ^{129}I) at off-site facilities that are located in geologic settings with low infiltration and do not have credible pathways to potable water aquifers.
- Provides flexibility in the available treatment technologies and disposal pathways, and reduces the potential for individual choke points to further delay the Hanford tank waste treatment and disposal mission. Concurrent LAW vitrification and solidification/immobilization treatment and disposal pathways would allow LAW routing based on waste characteristics to the most appropriate and efficient treatment technology.
- Provides opportunity to reduce or eliminate the need for future additional treatment capability and affords time to gain experience with the DFLAW vitrification process and grout solidification/ immobilization treatment prior to making such decisions.
- Minimizes financial demands and reduces mission duration and lifecycle costs.

Specific details for implementation of this recommendation will need to be identified through DOE processes, multi-party negotiations, and the National Environmental Policy Act (NEPA)[5] process. Regulatory and stakeholder participation procedures and government-to-government interactions with Tribal Nations[6] will need to be implemented using established formal processes.

This report describes the FFRDC team's analysis and results, which are intended to inform the decision-makers who will ultimately select approaches and technologies for supplemental LAW treatment and disposition.

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[5] *National Environmental Policy Act of 1969*, 42 USC 4321, et seq.

[6] Tribal Nation treaty rights at the Hanford Site are addressed by DOE and the Tribes through government-to-government consultations pursuant to DOE O 144.1, *Department of Energy American Indian Tribal Government Interactions and Policy*.

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^{3}H	hydrogen-3
^{14}C	carbon-14
^{79}Se	selenium-79
^{85}Kr	krypton-85
^{90}Sr	strontium-90
^{99}Tc	technetium-99
^{127}I	iodine-127
^{129}I	iodine-129
AAR	Association of American Railroads
ACI	American Concrete Institute
AEA	Atomic Energy Act
ALARA	as low as reasonably achievable
AoA	analysis of alternatives
ARP	actinide removal process
ASTM	ASTM International
BBI	Best Basis Inventory
BDAT	Best Demonstrated Available Technology
BFS	blast furnace slag
BSR	bench-scale reformer
BWF	Bulk Waste Disposal and Treatment Facilities
CAA	Clean Air Act
CAPEX	capital expenditure
CAW	Class A West
CBO	Congressional Budget Office
CD	Critical Decision
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CETL	Clemson Engineering Technologies Laboratory
CFR	Code of Federal Regulations
CIF	Consolidated Incineration Facility
CLSM	controlled low-strength material
CNWRA	Center for Nuclear Waste Regulatory Analysis
CO	carbon monoxide
CO	Colorado
CoC	contaminant of concern
CoPC	constituent of potential concern
Cr	chromium
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
CRR	carbon reduction reformer
Cs	cesium
CSSX	caustic-side solvent extraction

CST	crystalline silicotitanate
CSTR	continuous stirred tank reactor
CWA	Clean Water Act
D&D	decontamination and decommissioning
DBVS	Demonstration Bulk Vitrification System
DF	decontamination factor
DFHLW	direct-feed high-level waste
DFLAW	direct-feed low-activity waste
DMR	denitration and mineralizing reformer
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy, Office of Environmental Management
DOE-OPT	U.S. Department of Energy, Office of Packaging and Transportation
DOT	U.S. Department of Transportation
DRC	Division of Radiation Control
DRF	dry reagent formulation
DSS	double-shell slurry
DSSF	double-shell slurry feed
DST	double-shell tank
DU	depleted uranium
DWPF	Defense Waste Processing Facility
DWS	Drinking Water Standards
DWTS	dry waste transfer system
Ecology	Washington State Department of Ecology
EDTA	ethylenediamine-tetraacetic acid
EIS	environmental impact statement
EM	U.S. Department of Energy, Office of Environmental Management
EMCBC	U.S. Department of Energy, Environmental Management Consolidated Business Center
EMF	Effluent Management Facility
EPA	U.S. Environmental Protection Agency
ERDF	Environmental Restoration Disposal Facility
ETF	Effluent Treatment Facility
EWIS	Electronic Waste Information System
FA	fly ash
FBSR	fluidized bed steam reforming
FFRDC	Federally Funded Research and Development Center
FMF	Fuel Manufacturing Facility
FWF	Federal Waste Disposal Facility
FY	fiscal year
GAAT	Gunite and Associated Tanks
GAC	granular activated carbon
GAO	U.S. Government Accountability Office

GCL	geosynthetic clay liner
GDU	grout disposal unit
GFC	glass-forming chemical
GTCC	Greater-than-Class C
GWPL	groundwater protection level
GWQS	Ground Water Quality Standard
HEDTA	hydroxyethylethylenediaminetriacetic acid
HELP	Hydrologic Evaluation of Landfill Performance
HEPA	high-efficiency particulate air
HFPEM	High-Level Waste Feed Preparation and Effluent Management
HIC	high integrity container
HLVIT	high-level [mixed radioactive waste] vitrification
HLW	high-level waste
HRWR	high-range water reducer
HVAC	heating, ventilation, and air conditioning
HWMA	Hazardous Waste Management Act
I	iodine
IAEA	International Atomic Energy Agency
IC	institutional control
ICV	In-Container Vitrification[1]
IDF	Integrated Disposal Facility
ILAW	immobilized low-activity waste
ILW	intermediate level waste
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IOC	iron oxide catalyst
IP	industrial package
IQRPE	Independent Qualified Registered Professional Engineer
ISO	International Organization for Standardization
IWTU	Integrated Waste Treatment Unit
IX	ion exchange
K_d	dissociation constant
K_{sp}	solubility product constant
LANL	Los Alamos National Laboratory
LARW	low-activity radioactive waste
LAW	low-activity waste
LAWPS	Low-Activity Waste Pretreatment System
LAWST	low-activity waste supplemental treatment
LCC	lightweight cellular concrete
LCRS	leachate collection and removal system
LDR	Land Disposal Restrictions

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[1] In-Container Vitrification (ICV) is a trademark of Veolia, Boston, Massachusetts.

LDS	leak detection system
LERF	Liquid Effluent Retention Facility
LFE	low-activity waste feed evaporator
LLHH	long, large, and/or heavy hazardous
LLRW	low-level radioactive waste
LLW	low-level waste
LSA	low specific activity
LSW	liquid secondary waste
MCC	modular concrete canister
MCL	maximum contaminant level
MCU	modular caustic-side solvent extraction unit
MDL	method detection limit
MF	MasterFlow®
MIMS	Manifest Information Management System
MLLW	mixed low-level waste
MOE	measure of effectiveness
MST	monosodium titanate
MT	metric ton
NaOH	sodium hydroxide
NARM	naturally occurring and accelerator-produced radioactive material
NAS	National Academy of Sciences
NASEM	National Academy of Sciences, Engineering, and Medicine
NCP	National Contingency Plan
NDA	Nuclear Decommissioning Authority
NDAA	National Defense Authorization Act
NDAA17	Fiscal Year 2017 National Defense Authorization Act
NDAA21	Fiscal Year 2021 National Defense Authorization Act
NEPA	National Environmental Policy Act
NNSS	Nevada National Security Site
NORM	naturally occurring radioactive material
NO_x	nitrogen oxides
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NRSB	Nuclear and Radiation Studies Board
NSDWR	National Secondary Drinking Water Regulations
NY	New York
O	Order
OAG	Ogallala, Antlers, and Gatuna
OH	Ohio
OMB	U.S. Office of Management and Budget
OPC	ordinary portland cement
OPEX	operations expenditure

ORNL	Oak Ridge National Laboratory
ORP	U.S. Department of Energy, Office of River Protection
OU	Operable Unit
PA	performance assessment
PCB	polychlorinated biphenyl
PCT	product consistency test
PE	performance evaluation
Perma-Fix Northwest	Perma-Fix Northwest, Inc.
PGF	process gas filter
PNNL	Pacific Northwest National Laboratory
PT	Pretreatment Facility
PUF	pressurized unsaturated flow
PUREX	plutonium-uranium extraction
PV	present value
R&D	research and development
RADTRAN	Radioactive Material Transport
RCRA	Resource Conservation and Recovery Act
RCW	Revised Code of Washington
RD&D	research, development, and demonstration
REDOX	reduction-oxidation
RLWTF	Radioactive Liquid Waste Treatment Facility
RML	radioactive material license
ROD	record of decision
RPP	River Protection Project
SALDS	state-approved land disposal site
SAS	steam atomized scrubber
SBS	submerged bed scrubber
SBWW	sodium-bearing wastewater
SCDHEC	South Carolina Department of Health and Environmental Control
SCR	selective catalytic reduction
SDU	Saltstone Disposal Unit
SDWA	Safe Drinking Water Act
Se	selenium
SER	Safety Evaluation Report
SLAW	supplemental low-activity waste
SLDS	secondary leak detection system
SMCL	secondary maximum contaminant level
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SPF	Saltstone Production Facility
SPFT	single-pass flow-through

SPRU	Separations Process Research Unit
sRF	spherical resorcinol-formaldehyde
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SSR	Specific Safety Requirements
SST	single-shell tank
SSW	solid secondary waste
START	Stakeholder Tool for Assessing Radioactive Transportation
SVOA	semivolatile organic analyte
SVOC	semivolatile organic compound
SWPF	Salt Waste Processing Facility
TAC	Texas Administrative Code
TBI	Test Bed Initiative
Tc	technetium
TC&WM	Tank Closure and Waste Management
TCAS	Texas Constitution and Statutes
TCEQ	Texas Commission on Environmental Quality
TCLP	Toxicity Characteristic Leaching Procedure
TCO	thermal catalytic oxidizer
TDS	total dissolved solids
TEDF	Treated Effluent Disposal Facility
TFF	Tank Farm Facility
TFPT	Tank Farms Pretreatment
THOREX	thorium extraction
TI	transportation index
TO	thermal oxidizer
TOC	total organic carbon
TOE	total operating efficiency
TPA	Tri-Party Agreement
TRAGIS	Transportation Routing Analysis Geographic Information System
TRL	technology readiness level
TRU	transuranic
TSCR	tank-side cesium removal
TSD	treatment, storage, and disposal
TSDF	Texas Storage and Processing Facility
TVS	Transportable Vitrification System
TWINS	Tank Waste Information Network System
TX	Texas
U.K.	United Kingdom
U.S.	United States
UAC	Utah Administrative Code
UDEQ	Utah Department of Environmental Quality

UMTRA	Uranium Mill Tailings Remediation Action
UT	Utah
UTS	Universal Treatment Standards
UV/OX	ultraviolet/oxidation
UWQB	Utah Water Quality Board
VHT	vapor hydration test
VLAW	vitrified low-activity waste
VOA	volatile organic analyte
VOC	volatile organic compound
VSL	Vitreous State Laboratory of The Catholic University of America
VTD	vacuum thermal desorption
WA	Washington
WAC	Washington Administrative Code
WCS	Waste Control Specialists, LLC
WDOH	Washington Department of Health
WebTRAGIS	Web-Based Transportation Routing Analysis Geographic Information System
WESP	wet electrostatic precipitator
WIPP	Waste Isolation Pilot Plant
WIR	Waste Incidental to Reprocessing
WRF	waste receiving facility
WRPS	Washington River Protection Solutions, LLC
WTP	Waste Treatment and Immobilization Plant
WVDP	West Valley Demonstration Project
XAS	X-ray absorption spectroscopy

1.0 INTRODUCTION

Section 3125 of the Fiscal Year 2021 National Defense Authorization Act (NDAA21), directs the U.S. Department of Energy (DOE) to enter into an arrangement with a Federally Funded Research and Development Center (FFRDC) to conduct an analysis that:

> "*…shall be designed, to the greatest extent possible, to provide decisionmakers with the ability to make a direct comparison between approaches for the supplemental treatment of low-activity waste at the Hanford Nuclear Reservation based on criteria that are relevant to decision making and most clearly differentiate between approaches.*"

In accordance with Section 3125, this analysis provides an assessment of the following:

- The most effective potential technology for supplemental treatment of low-activity waste (LAW) that will produce an effective waste form
- The differences among approaches for the supplemental treatment of LAW considered as of the date of the analysis
- The compliance of such approaches with the technical standards described in Section 3134 of the NDAA for Fiscal Year 2017 (NDAA17)
- The differences among potential disposal sites for the waste form produced through such treatment, including mitigation of radionuclides, including technetium-99 (^{99}Tc), selenium-79 (^{79}Se), and iodine-129 (^{129}I), on a system level
- Potential modifications to the design of facilities to enhance performance with respect to disposal of the waste form to account for: (1) regulatory compliance, (2) public acceptance, (3) cost, (4) safety, (5) expected radiation dose to maximally exposed individuals over time, and (6) differences among disposal environments
- Approximately how much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals to reduce disposal costs for radionuclides
- Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level by the performance assessment of a potential disposal site and, if the radionuclides cannot be left in the waste form, how to account for the secondary waste stream
- Other relevant factors relating to the technology, including: (1) costs and risks in delays with respect to tank performance over time, (2) consideration of experience with treatment methods at other sites and commercial facilities, and (3) outcomes of the DOE Office of Environmental Management Test Bed Initiative at Hanford.

In addition, Section 3125 of NDAA21 requires the FFRDC team to perform additional analysis of grout treatment options building on the analysis in the FFRDC report for Section 3134 of NDAA17. Because this is a follow-on analysis, some of the summary and overview information presented is repeated from the NDAA17 analysis.

Congress, in NDAA17 Section 3134, defines supplemental LAW as "the portion of low-activity waste at the Hanford Nuclear Reservation, Richland, Washington, that, as of such date of enactment, [December 23, 2016] is intended for supplemental treatment."[1] DOE's ORP-11242, *River Protection Project System Plan* (System Plan, Rev. 7), in effect on the date of enactment, identified the portion of LAW intended for supplemental treatment as: LAW that the Waste Treatment and Immobilization Plant (WTP) LAW Vitrification Facility is predicted to lack the capacity to treat without impacting the duration of the WTP high-level waste (HLW) Vitrification Facility mission. Consistent with this definition, the FFRDC follow-on report addresses alternatives to augment LAW treatment capacity for the quantity of the low-activity fraction of Hanford tank waste (LAW) that has been estimated for which the treatment capacity in the WTP LAW Vitrification Facility will be insufficient. However, the most recent System Plan (ORP-11242, Rev. 9) information was used in this analysis to include the most up-to-date information.

The focus of the FFRDC analysis is on technologies and approaches, and the FFRDC team is made up of technical experts in appropriate disciplines from the national laboratories, academia, industry, and private institutions. The NDAA21 also requires a concurrent review of the analysis by a committee of technical experts selected by the National Academy of Sciences, Engineering, and Medicine (NASEM).

This report describes the FFRDC team's analysis and results, which are intended to inform the decision-makers who will ultimately select approaches and technologies for supplemental LAW treatment and disposition.

1.1 Supplemental Treatment for Low-Activity Waste

The Hanford Site, in southeast Washington State, currently stores approximately 56,000,000 gallons (56 Mgal [210 million L]) of radioactive and chemically hazardous wastes in underground storage tanks located in 17 tank farms. Tank wastes will be divided into a high-activity fraction for treatment and disposal in a geologic repository designated for spent nuclear fuel and HLW, and a low-activity fraction of tank waste for subsequent treatment and disposition in a mixed low-level waste (MLLW) disposal facility. A waste processing and treatment facility, the WTP, will include the HLW Vitrification Facility for immobilizing the high-activity fraction and the WTP LAW Vitrification Facility for immobilizing the low-activity fraction. Both facilities will use vitrification technology to immobilize the Hanford tank wastes in a glass waste form.

The System Plan (ORP-11242) estimates that the expected WTP LAW vitrification treatment capacity will not be able to treat all the LAW expected to be generated during the tank waste mission, with a shortfall in LAW treatment capacity of approximately one half of the LAW volume (56 Mgal [210 million L][2]). To maintain the tank waste processing mission schedule duration specified in the baseline case of ORP-11242 (Rev. 9), DOE will require additional LAW treatment capacity (termed "supplemental LAW") external to the WTP process. The LAW must be solidified by a treatment technology before the waste can be permanently disposed of in an approved DOE on-site disposal facility or a commercial (state or U.S. Nuclear Regulatory Commission [NRC]-licensed) off-site MLLW disposal facility.

LAW is characterized as a "mixed waste" containing both radioactive and hazardous chemical constituents. Compared to the high-activity fraction of tank waste, the overall radioactivity content of the LAW is significantly lower. Pretreatment includes filtration for solids removal and removal of cesium by ion exchange (IX) using an elutable resin or absorption onto crystalline silicotitanate (CST). The LAW treatment process concludes with immobilization of the waste into a solid form (e.g., glass, grout) prior to disposal. The requirements for the immobilized form will vary depending on the disposal site.

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[1] NDAA21 Section 3125, which governs the FFRDC follow-on report, refers to NDAA17 Section 3134.

[2] The volume of waste to be treated is much greater than the volume currently in the waste tanks because water is added during retrieval, staging, and pretreatment processes.

Some of the metals and organic chemicals expected to be in LAW are regulated under the *Resource Conservation and Recovery Act of 1976* (RCRA), which sets Land Disposal Restriction (LDR) standards that must be met through treatment or other regulatorily approved approaches. Other constituents, such as nitrates, are regulated through *Safe Drinking Water Act of 1974* (SDWA) limits, which establish maximum contaminant levels for these constituents.

LAW treatment and disposal must meet requirements established for protection of human health and the environment, including specifically for (1) metals and organic chemicals (established under RCRA), (2) radionuclides (established under the *Atomic Energy Act of 1954* [AEA]), and (3) additional chemicals (e.g., nitrates) (as established under state and other federal regulations).

1.2 Waste Treatment Technologies Analyzed

The three primary LAW treatment technologies identified in the NDAA21 (and NDAA17) for analysis are vitrification, fluidized bed steam reforming (FBSR), and grouting. However, each of these primary immobilization technologies has different processing steps to achieve implementation, including pretreatment steps, offgas and effluent treatment prior to discharge to the environment, and treatment and disposal of liquid and solid wastes that contain constituents requiring immobilization prior to disposal in a licensed/permitted land disposal facility.

Vitrification – This high-temperature technology blends the liquid LAW with glass-forming materials at approximately 1,150°C, forming a mixture that incorporates the radionuclides and metals into a “primary” monolithic glass waste form, but significant fractions of semi-volatile species are emitted from the melter requiring an extensive offgas treatment system to capture these species and mitigate release to the stack. The vitrification and offgas systems destroy most LDR organic compounds and some of the nitrates. Because the water in the LAW is not incorporated into the glass, practically all the water initially present in LAW and produced in the process, primarily from operations of the offgas system, is managed as liquid “secondary” waste, which contains radionuclides, metals, and organic chemicals not captured or destroyed by the glass-forming process step.

The solid secondary wastes (e.g., offgas filters, activated carbon, used equipment) from the vitrification process would be embedded in cementitious material (similar to the “Grouting” description below) prior to disposal, while some of the liquid secondary wastes will be immobilized using grouting for subsequent disposal and some will be treated with other wastewater streams, with the treated wastewater released in accordance with approved discharge permits. DOE has successfully operated tank waste vitrification facilities for the high-activity fraction of tank waste at the Savannah River Site (SRS) and the West Valley Demonstration Project (WVDP), but the HLW streams were significantly different from Hanford LAW and throughput requirements were much lower.

Fluidized bed steam reforming – This high temperature technology blends the liquid LAW with dry fuel materials and inorganic materials at approximately 750°C, to react, form, and incorporate most of the radionuclides and metals into dry granular mineral particles. The granular particles can be further encapsulated in a cement-like geopolymer. A dry, catalytic offgas treatment system is used, so no liquid offgas system secondary wastes are produced. Solid secondary wastes (spent carbon sorbent and air filters) are similar to those from vitrification but are anticipated to have less radioactivity because of improved capture and lower operating temperatures. FBSR is expected to destroy essentially all LDR organic compounds and nitrates, converting them to carbon dioxide, nitrogen, water, and residual nitrogen oxides (NO_x). DOE has constructed an FBSR facility for treating wastes with different characteristics from Hanford LAW at the Idaho National Laboratory (INL), which is expected to begin operations to treat approximately 900,000 gallons (3.4 million L) of tank waste in 2023.

Grouting – This technology operates at room temperatures and blends the LAW with dry inorganic materials (e.g., portland cement and blast furnace slag) to produce a monolithic cement-like waste form. Pretreatment may be required to destroy or separate LDR organic chemicals if concentrations are measured/determined to be above the regulatory limits. Radionuclides, metals, and nitrates are incorporated into the grout. Secondary wastes from this process are minimal because the water in the LAW is chemically incorporated into the waste form. Grouting systems that have operated throughout the DOE complex include two low-activity tank waste facilities at SRS and WVDP. Grouting is a common practice for treating commercial low-level radioactive waste and is a U.S. Environmental Protection Agency (EPA)-recommended and common practice for wastes containing metals and other inorganic components.

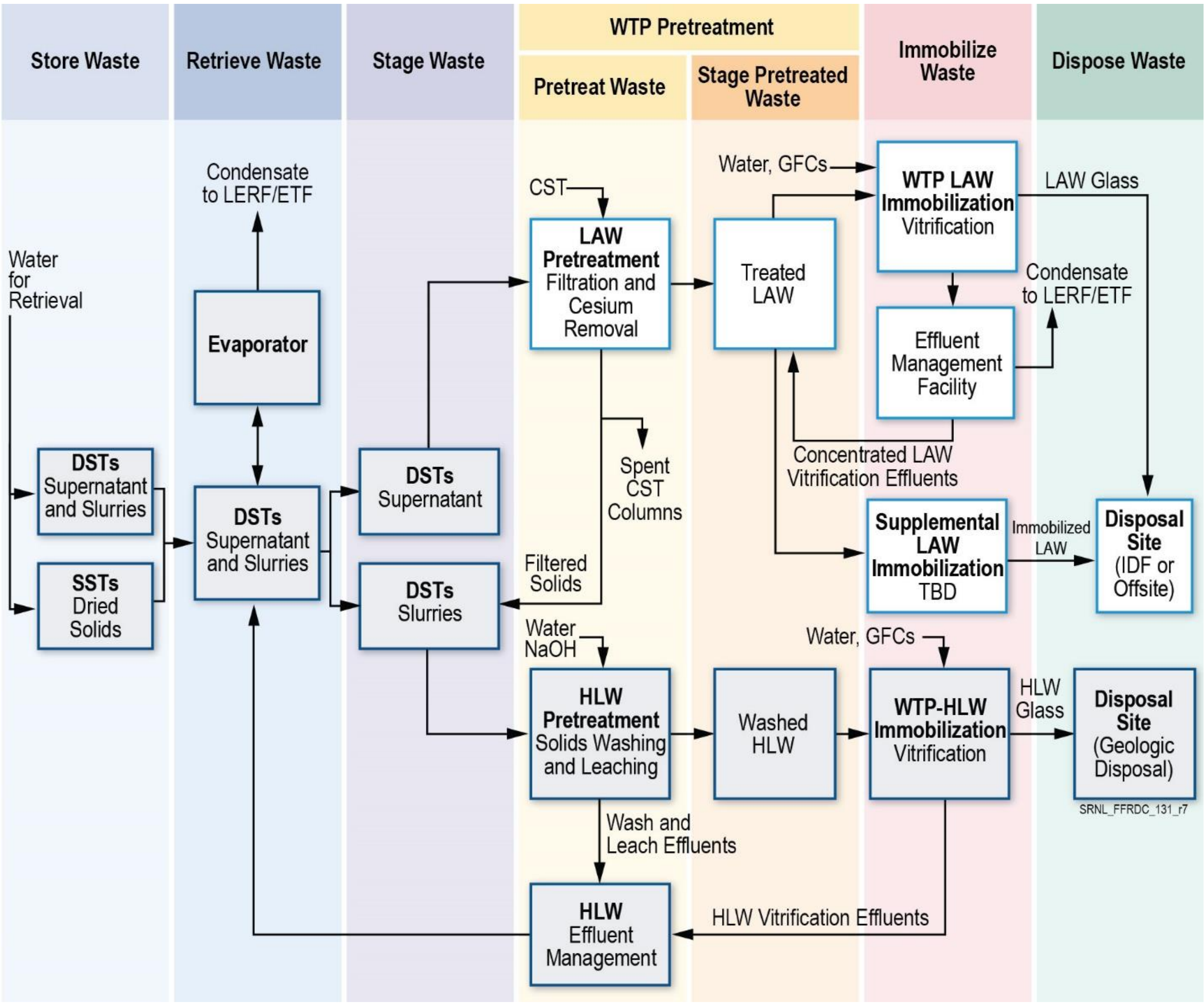
1.3 Process Overview

1.3.1 Overall Hanford Waste Treatment Process Overview

Supplemental treatment of LAW is a portion of a larger program to retrieve, qualify and stage, pretreat, immobilize, and dispose of wastes from plutonium production at the Hanford Site. Some of the waste is currently stored as “dried” solids, called sludge or saltcake depending on the salt content, in the single-shell tanks (SST) (some supernatant liquid remains in SSTs but bulk free liquid has been removed), with the remaining portion stored as slurry or supernatant liquid in DSTs. A simplified flowsheet is shown in Figure 1.3-1 (on the next page), assuming a direct-feed HLW (DFHLW) treatment configuration. The WTP Pretreatment (PT) Facility performs the “pretreat waste” and “stage pretreated waste” functions and the effluent management for the LAW and HLW processes, but a direct-feed approach was used in the scenarios in this evaluation.

The first step in the waste treatment process is retrieval of the saltcake and sludge from the SSTs into a double-shell tank (DST), typically done by sluicing with supernatant liquids or water. Large volumes of water could be added during this process and solid salts are dissolved. Solids that remain after the water addition contain most of the long-lived radionuclides, so a solid-liquid separation is performed with resulting liquid waste staged for additional pretreatment to remove cesium while the solids are staged for additional pretreatment to further reduce the amount of salts in the slurry remaining after decanting the supernatant liquid waste (the remaining slurry is often referred to as sludge). The supernatant fraction is typically described as treated LAW once the cesium is removed, while the slurry remaining after decanting the supernatant liquid is the high-activity fraction.

Pretreatment of the high-activity fraction consists of sludge “washing”, which removes additional salts from the sludge through successive addition of water and solids/liquid separation to remove additional supernatant liquid. In addition, dissolution of aluminum species from the solids using caustic leaching processes may be performed. Both the washing and leaching operations will generate additional supernatant liquid as part of the LAW that will be sent to the LAW pretreatment processes for cesium removal. The high-activity fraction (washed and/or leached slurry) will be vitrified in the WTP HLW Vitrification Facility, with the immobilized waste stored onsite until transport to a geologic disposal site. Vitrification processes do not immobilize the water from the slurries; the water is evaporated from the melter and then condensed from the melter offgas and collected along with water added during offgas treatment processes. The effluents from the WTP HLW Vitrification Facility and the WTP LAW Vitrification Facility processes will be recycled for immobilization into the glass or can be dispositioned in other ways if necessary.



CST = crystalline silicotitanate.
DST = double-shell tank.
ETF = Effluent Treatment Facility.
GFC = glass-forming chemical.
HLW = high-level waste.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
LERF = Liquid Effluent Retention Facility,
NaOH = sodium hydroxide.
SST = single-shell tank.
WTP = Waste Treatment and Immobilization Plant.

Figure 1.3-1. Simplified Diagram of Planned Tank Waste Treatment (Showing Direct-Feed High-Level Waste Process)

An evaporation process is assumed to concentrate the dilute WTP HLW Vitrification Facility effluents prior to sending these streams to LAW pretreatment, although some WTP HLW Vitrification Facility treatment streams may require processing as relatively dilute streams to prevent precipitation.

LAW pretreatment consists of filtration to remove any residual solids from the supernatant liquid, followed by cesium removal. This evaluation assumes that cesium removal is performed using CST sorbent using systems similar to the currently operating tank-side cesium removal (TSCR) unit, but the WTP PT Facility would use a different resin and would not remove the strontium. The treated LAW will be sent to the existing WTP LAW Vitrification Facility and the supplemental LAW treatment facility.

Current models assume that the WTP LAW Vitrification Facility is fed preferentially, with only remaining excess LAW sent to supplemental treatment, although this study also considers availability of parallel treatment process pathways by WTP LAW vitrification and supplemental LAW treatment where LAW can be routed to either process based on waste characteristics to achieve improved processing efficiency. The immobilized LAW will be disposed of in the existing Integrated Disposal Facility (IDF) at the Hanford Site or existing MLLW off-site disposal facilities. Liquid effluents from the WTP LAW Vitrification Facility are transferred to the Effluent Management Facility (EMF) where the effluents are evaporated from the primary offgas system. The concentrate is recycled to the WTP LAW Vitrification Facility for subsequent immobilization, while the condensate is sent to the Hanford Liquid Effluent Retention Facility/Effluent Treatment Facility (LERF/ETF) for subsequent processing and disposition.[3]

The overall tank waste treatment program continues to evolve over time, and these changes impact the volume, composition, and schedule of LAW feed that would be sent to the supplemental LAW treatment facility. Factors that influence the overall LAW mission include the timing and extent of HLW pretreatment processes, start date and achieved WTP LAW throughput during direct-feed low-activity waste (DFLAW) processing, and the efficiency of existing facilities (e.g., tank farms, 242-A Evaporator, LERF/ETF) to manage SST retrievals, waste staging and characterization, and effluent treatment. This document used schedules available in early 2022. Any changes in the WTP LAW Vitrification Facility or other tank waste treatment schedules that are not incorporated into the System Plan (ORP-11242, Rev. 9) models are not addressed.

The purpose of this document is to provide comparisons of LAW supplemental treatment technologies and capabilities, some of which are not necessarily impacted by WTP LAW vitrification processing. Demonstrating and implementing early treatment and disposal options discussed herein would help to mitigate the risk of continued tank waste storage.

1.3.1.1 Composition and Volume of Low-Activity Waste Feed to Supplemental Treatment of Low-Activity Waste

The composition and volume of feed sent to the supplemental treatment facility for LAW is highly dependent on the assumptions made for the overall flowsheet. As stated above, the sequence of tank retrievals, the amount of washing and leaching of high-activity fraction slurries, and the timing of the start of WTP HLW Vitrification Facility processing, all impact the volume of LAW to be treated. In addition, the timing of implementing the supplemental LAW treatment capability impacts the monthly volume and composition of the feed designated for supplemental treatment. Thus, any description of the feed to the facility is subject to uncertainty.

System Plan, Scenario 1B (ORP-11242, Rev. 9) was used to specify the feed vector (feed volume and composition over time) for this evaluation, and this feed vector was used to perform the initial evaluation of all alternatives. The feed vector information provided by WRPS includes monthly average volumes and compositions for the expected feed to the supplemental LAW treatment facility.

Using a fixed benchmark budget scenario, vitrification was projected to begin operations much later than the dates assumed for supplemental LAW in the System Plan, while several grout alternatives offer opportunities for an early start. To better understand the impacts of the supplemental LAW schedule on the overall and supplemental LAW missions, TOPSim model runs were performed by Washington River Protection Solutions, LLC (WRPS) in support of the supplemental LAW evaluation.

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[3] The LERF/ETF provides treatment (e.g., ultraviolet/oxidation [UV/OX], filtration, ion exchange, organics separation, evaporation) of liquid effluents from existing processes, such as the 242-A Evaporator condensate, and will treat effluents from the WTP and IDF. The treated water under DFLAW will be disposed of in the State Approved Land Disposal Site (SALDS) at Hanford, while extracted contaminants are either captured in the ETF secondary treatment train that is concentrated via evaporation (brine concentrate) or is managed separately (steam stripper effluent). Brine concentrate and steam stripper effluent is then grouted for disposal at IDF. Effluents sent to LERF/ETF must meet the facility waste acceptance criteria.

These runs were used to evaluate the efficacy and impact of an early start and the impact of a fixed benchmark budget. Alternatives for FBSR were not remodeled, as the timing of the supplemental LAW implementation for FBSR was expected to more closely match the System Plan model than the other alternatives. The updated model runs were used to support capital and operating costs, but were not used for shipping or waste disposal evaluations. All shipping and waste disposal evaluations used the System Plan (Rev. 9) feed vector.

The System Plan, Scenario 1B, assumed that the WTP PT Facility was in service, whereas an assumption during this assessment was that TSCR units (or similar) would be used for LAW pretreatment. Two significant differences in the feed vector would result from the change in pretreatment system technology. First, the PT Facility design included evaporators that concentrated the feed after cesium removal. This evaporation step *is included* in the *LAW supplemental* facility functionality *in all alternatives* to minimize the impact on the waste volume to be treated. Second, the cesium removal process via absorption on CST media will also remove most of the strontium and significant portions of other species, such as plutonium. Adjustments in this analysis were made to the strontium content of the feed, but no other adjustments were made to account for removal of other species.

Table 1.3-1 and Table 1.3-2 show the feed compositions for major chemical and radiological components, and Figure 1.3-2 (on the next page) shows the expected variations in volume for the System Plan (Rev. 9), Scenario 1B feed vector.

Table 1.3-1. Chemical Species in Pretreated Low-Activity Waste (Scenario 1B)

Analyte	Average	Maximum	Minimum	Units
Sodium	160	180	120	g/L
Nitrate	110	200	29	g/L
Free Hydroxide	49	88	7.6	g/L
Nitrite	28	64	6.3	g/L
Carbonate	17	45	3.2	g/L
Aluminum	11	26	1.3	g/L
TOC	5.3	78	0.49	g/L
Fluorine	3.6	14	0.10	g/L
Phosphate	3.3	13	0.24	g/L
Oxalate	3.1	14	0.34	g/L
Sulfur	2.8	8.6	0.81	g/L
Chlorine	1.7	4.2	0.46	g/L
Potassium	1.2	6.5	0.17	g/L
Silicon	0.66	3.7	0.047	g/L

Source: Scenario 1B of ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.
TOC = total organic carbon.

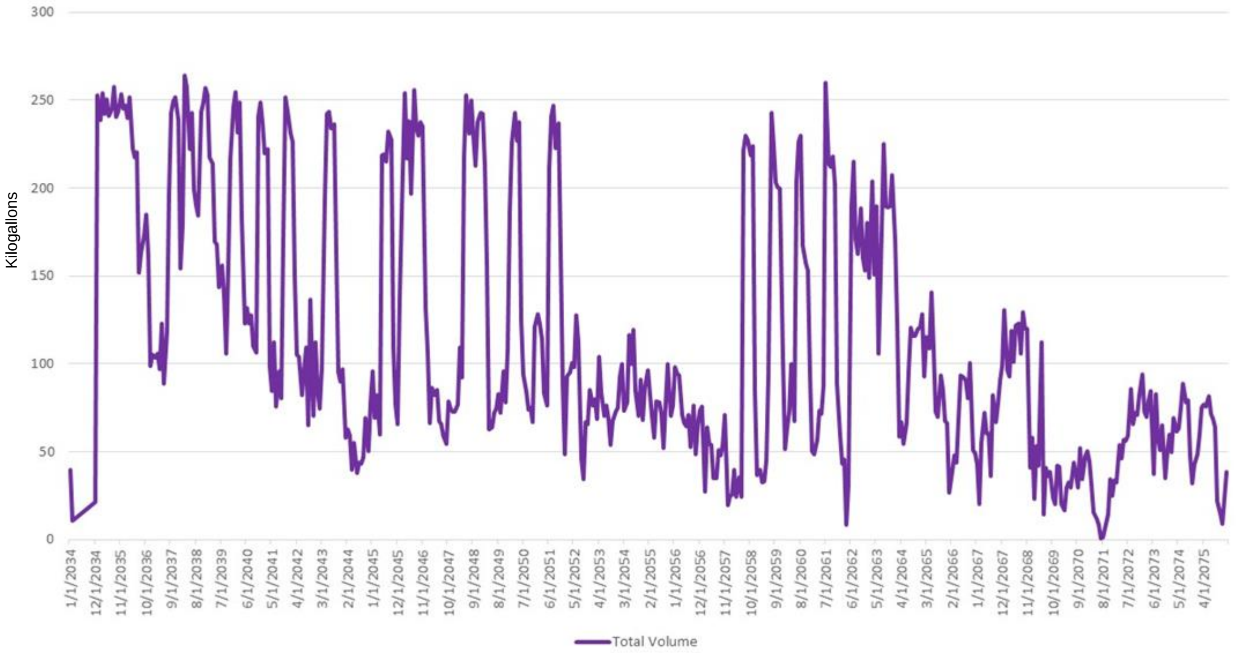
The “Adjusted Amount” in Table 1.3-2 adjusts the ^{90}Sr amount to account for a decontamination factor (DF) of 100 assumed for the ^{90}Sr absorption in TSCR for non-complexant waste for the System Plan Scenario 1B feed vector. Complexant waste is assumed to have a lower DF for strontium, so the adjustment is based only on its removal from non-complexant waste for LAW supplemental treatment. This study assumes complexant waste could be sent to the WTP LAW melter if it is not compatible with grouting.

Table 1.3-2. Radionuclides in Pretreated Low-Activity Waste Specified for Supplemental Treatment in System Plan (Rev. 9) Scenario 1B

Radionuclide	Total Amount in Supplemental LAW Feed[a] (Ci)	Adjusted Amount (Ci)	Radionuclide	Total Amount in Supplemental LAW Feed[a] (Ci)	Adjusted Amount (Ci)
^{90}Sr	300,000	3,000	^{234}U	5.3	5.3
^{151}Sm	51,000	51,000	^{238}U	5.3	5.3
^{99}Tc	12,000	12,000	^{242}Cm	4.6	4.6
^{63}Ni	5,900	5,900	^{237}Np	4.4	4.4
^{137}Cs	1,500	1,500	^{244}Cm	3.3	3.3
^{241}Am	1,300	1,300	^{60}Co	2.2	2.2
^{93}Zr	460	460	^{152}Eu	2.1	2.1
^{93m}Nb	460	460	^{155}Eu	2.0	2.0
^{14}C	350	350	^{243}Am	0.63	0.63
^{239}Pu	320	320	^{231}Pa	0.48	0.48
^{79}Se	220	220	^{227}Ac	0.32	0.32
^{59}Ni	110	110	^{125}Sb	0.24	0.24
^{126}Sn	95	95	^{243}Cm	0.24	0.24
^{113m}Cd	89	89	^{235}U	0.22	0.22
^{241}Pu	88	88	^{236}U	0.14	0.14
^{240}Pu	68	68	^{232}U	0.13	0.13
^{3}H	48	48	^{228}Ra	0.047	0.047
^{154}Eu	26	26	^{232}Th	0.039	0.039
^{233}U	15	15	^{242}Pu	0.031	0.031
^{129}I	12	12	^{229}Th	0.027	0.027
^{238}Pu	12	12	^{226}Ra	0.00015	0.00015

[a] ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

LAW = low-activity waste.



Source: ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

Figure 1.3-2. Monthly Volume Fed to Supplemental Low-Activity Waste Treatment (kilogallons)

Although no adjustments were made in Table 1.3-2 for ^{151}Sm, the concentration is expected to be significantly lower in concentration because the amount reported in the feed vector does not accurately account for its low solubility. Similarly, removal of the plutonium and neptunium isotopes from non-complexant waste is not adjusted in Table 1.3-2, even though CST is known to remove over 50% of each (PNNL-28783, *Dead-End Filtration and Crystalline Silicotitanate Cesium Ion Exchange with Hanford Tank Waste AW-102*; PNNL-27706, *Cesium Ion Exchange Testing Using Crystalline Silicotitanate with Hanford Tank Waste 241-AP-107*; and PNNL-30712, *Ion Exchange Processing of AP-105 Hanford Tank Waste through Crystalline Silicotitanate in a Staged 2- then 3-Column System*). Removal of these isotopes would not change the NRC waste classification of the liquid. Additional details for the feed vector are described in Volume II, Appendix B.

1.3.1.2 Mission Length and Required Supplemental Low-Activity Waste Treatment Capacity

As shown in Figure 1.3-2, per System Plan Scenario 1B (ORP-11242, Rev. 9), the supplemental LAW treatment facility begins operating in 2034 and operates through 2075. As with the volume and composition, the mission duration for the supplemental LAW treatment facility will be impacted by the assumptions made for WTP HLW Vitrification Facility processing and tank sequencing. In most scenarios, the WTP HLW Vitrification Facility mission determines the overall River Protection Project (RPP) mission length, with little impact from the supplemental LAW treatment capability. However, these scenarios assume that the supplemental LAW treatment capacity is set so that the WTP HLW Vitrification Facility mission is not impacted. If supplement LAW treatment capacity is less than the amount needed in a given month, waste processing at the WTP HLW Vitrification Facility will be impacted and the mission length extended. Therefore, the required capacity for the supplemental LAW treatment is based on the maximum amount to be processed in a month during the overall RPP mission.

The date for HLW melter startup is set at December 31, 2033, by Consent Decree (2022). The ramp-up rate of the HLW melters can vary between modeling runs due to several factors, so the exact need date for the LAW supplemental treatment capability varies accordingly. In the model run performed for this report (MR-50713, *NDAA LAWST Modeling Study*), the HLW melter begins operation at 57% of rated capacity and ramps to 100% of rated capacity at the end of 2038.

Setting the capacity of the supplemental LAW facility at the monthly maximum will result in operation of the facility at less than design capacity for most of the supplemental LAW mission. As a result, supplemental LAW processes that can maintain operational efficiency even at reduced capacity or that can be easily started and stopped would be beneficial.

Note that delaying the start of supplemental LAW treatment can increase the required capacity of supplemental LAW treatment and delays the WTP HLW Vitrification Facility mission since the WTP HLW Vitrification Facility will run at reduced capacity until the supplemental LAW treatment facility is started. Other aspects of the tank waste treatment program, such as SST retrievals, could also be impacted by delays in supplemental LAW treatment. Figure 1.3-3 provides a linkage of the potential mission completion dates with and without LAW supplemental treatment and as a function of the LAW supplemental facility start-up dates. System planning modeling efforts, somewhat analogous to those employed by DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC&WM EIS) (and associated Reader's Guide and Summary), indicate that without LAW supplemental treatment, the tank waste mission could potentially extend well beyond 2090, facilitating the potential need to replace the WTP complex at least once. Figure 1.3-3 also depicts an opportunity for an "Early Start" approach, in which alternatives entailing off-site disposal could allow for supplemental LAW treatment to begin as early as 2027.

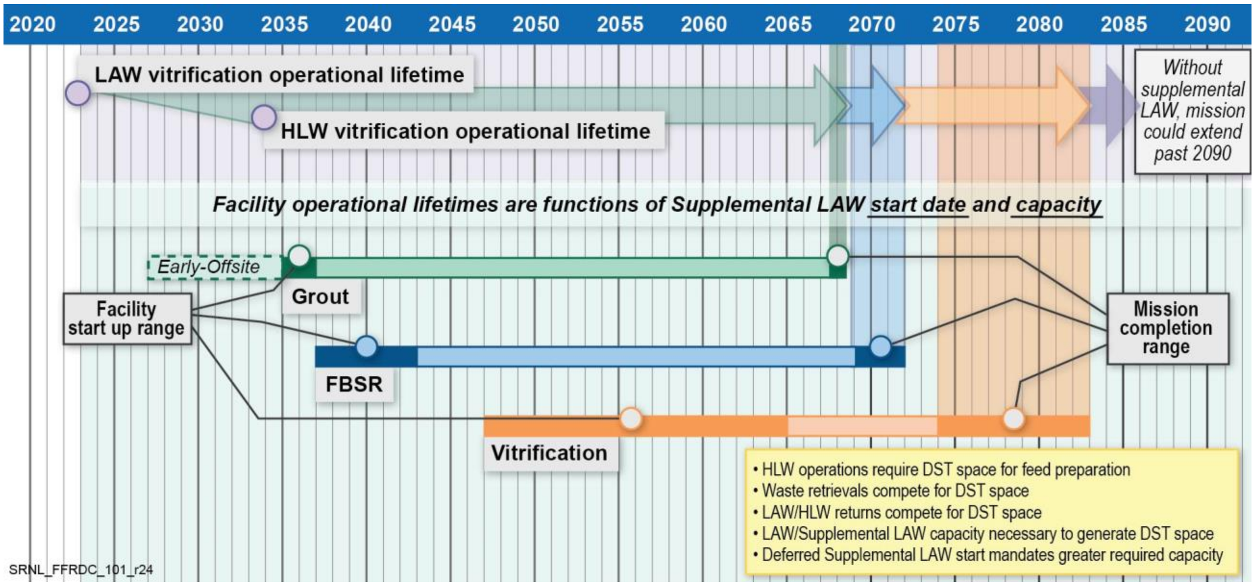
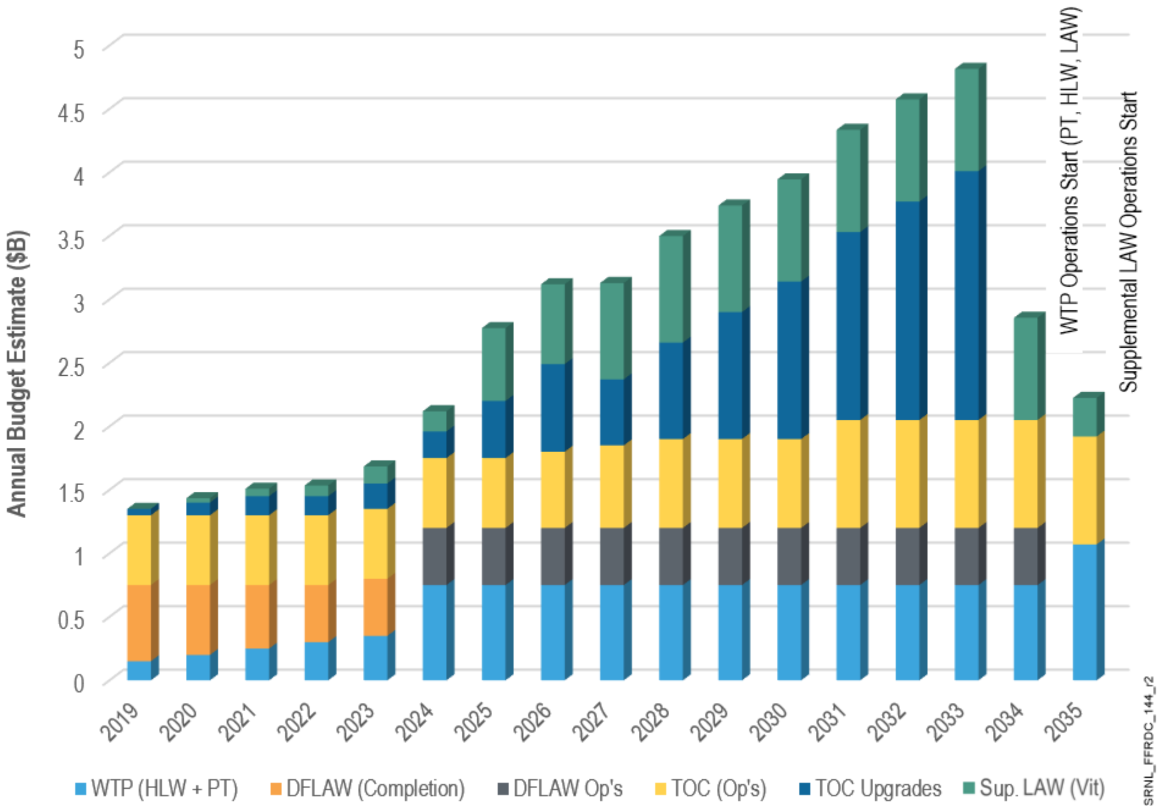


Figure 1.3-3. Relationship Between Low-Activity Waste Supplemental Treatment Start Date and Projected Tank Waste Mission Completion Date

As previously described, the tank waste cleanup mission is paced by vitrification of the tank waste sludge portion via the WTP HLW Vitrification Facility. HLW vitrification requires feed preparation to increase solids content and remove a large fraction of the soluble sodium salts – that volume is delivered to the WTP LAW Vitrification Facility and to LAW supplemental treatment for processing and disposition. HLW feed preparation requires processing capability and DST space. DST space is also required to consolidate and store the incoming waste volume from SST retrievals. Further, space is required to store HLW vitrification effluent and integrate that volume via feed preparation and LAW processing. All of these actions must be integrated with production capability and rates. The focus of LAW supplemental treatment is to increase the work-off rate of the tank waste volume to support the overall retrieval/storage/preparation system capacity – allowing HLW vitrification to effectively pace the RPP clean-up mission. Per Figure 1.3-3, LAW supplemental treatment operations are assumed to be unconstrained by either feed preparation or funding.

The previous NDAA report (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*) provided the matching unconstrained near-term funding necessary to provide this suite of capabilities, as projected in 2018 – as reproduced in Figure 1.3-4. The confluence of capital projects, specifically the completion of WTP and Hanford tank farms upgrades, in addition to LAW supplemental treatment as vitrification, when added to the expected operations cost for DFLAW processing, represent a risk to successful LAW supplemental treatment.

Figure 1.3-3 illustrates this point as the timeline links the projected start-up dates for various LAW supplemental treatment processes, with the concordant impact to the overall processing mission schedule. Based on the modeling results from previous work (and consistent with the results summarized in the TC&WM EIS [DOE/EIS-0391]), HLW vitrification, when operational, is significantly limited without the supporting capability provided by LAW supplemental treatment. A rough assessment indicates that the WTP HLW Vitrification Facility will be limited to one-half throughput—in other words, every 2 years of HLW facility operations without LAW supplemental treatment adds 1 year to the overall mission (MR-50713). Constraining the start-up dates of LAW supplemental treatment (as a function of project cost and schedule) will therefore significantly impact the completion date for waste treatment.



Source: Figure 1 of SRNL-RP-2018-00687, 2019, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*, Savannah River National Laboratory, Aiken, South Carolina.

Figure 1.3-4. Unconstrained Funding Profile (Unescalated) Reflecting the Major Cost Elements Leading to Full Hanford Mission Operations

As the LAW supplemental treatment dates are a function of facility cost, higher facility costs carry the risk of a later starting date (and larger range thereof), more HLW vitrification years at lower capacity, and a longer total mission duration with concordantly higher cost. Conversely, if LAW supplemental treatment can be facilitated without large capital projects, start dates prior to 2035 would allow use of available DST space for feed preparation (LAW and HLW) and to support retrievals.

A Hanford tank waste treatment mission that extends until 2075 or beyond requires the treatment facilities to be built for the expected mission length, and also requires an extended life for the existing facilities and systems that will support the mission. The waste storage SSTs and some of the DSTs have already exceeded their design life, and the risk of additional tank leaks is a significant concern given the length of time needed to complete Hanford tank waste treatment.

1.3.2 Hanford Tank Leaks

Some of the waste storage tanks at Hanford have leaked in the past, and the risk of future emerging additional leaking tanks exists given the expected duration of the tank waste treatment mission. This analysis recognizes this condition but does not attempt to predict or model the timing or extent of future leaks, although removing waste sooner would reduce the probability of a tank leak. The Hanford Site has extensive surveillance and monitoring protocols and other tank integrity programs in compliance with DOE M 435.1-1, *Radioactive Waste Management Manual*, to monitor the status of the tanks and reduce the risk of future leaks; these programs are described in RPP-7574, *Double-Shell Tank Integrity Program Plan*, and RPP-PLAN-60765, *Single-Shell Tank Integrity Program Plan.*

Tank Farms and Leaks

The Hanford waste tank farms (groups of tanks) were constructed to store waste generated from reprocessing spent nuclear fuel to recover plutonium, with the first tank farms entering service in 1944. These tanks are typically 75 ft in diameter, with varying height to achieve 530, 758, or 1,000 kilogallon capacity,[4] and are buried 6–8 ft below grade (CNWRA-97-001, *Hanford Tank Waste Remediation System Familiarization Report*). Initially, single-walled (or single-shelled) tanks (technically, a concrete vault with a carbon steel liner) were constructed with a total of 149 SSTs entering service during the 1940s, 1950s, and 1960s. In the late 1960s, tank construction shifted to the use of double-walled (or double-shelled) tanks, with 28 tanks completed between 1970 and 1986 (PNNL-13605, *A Short History of Hanford Waste Generation, Storage, and Release*). Many of the SSTs developed leak sites or are assumed to have leak sites, as shown in Table 1.3-3. Note that a leak site does not imply an active leak. The tank waste level could be below the leak site or interim stabilization methods (described below) taken to mitigate leaks have prevented or mitigated leaks from the leak site. One of the oldest DSTs, Tank AY-102, developed a leak in the interior tank (waste was noted in the annular space between the inner and outer tanks).

Table 1.3-3. Hanford Tank Farms

Farm	Years built	Number of tanks	Tank type	Quadrant	Assumed or Confirmed Past Leakers	Comments
T	1943-1944	16	SST	NW	5	
TX	1947-1948	18	SST	NW	6	
TY	1951-1952	6	SST	NW	5	
B	1943-1944	16	SST	NE	11	
BX	1946-1947	12	SST	NE	5	
BY	1948-1949	12	SST	NE	5	
C	1943-1944	16	SST	SE	6	Retrieval complete – awaiting closure
U	1943-1944	16	SST	SW	4	
S	1950-1951	12	SST	SW	0	Tank S-122 retrieval complete
SX	1953-1955	15	SST	SW	8	
SY	1974-1976	3	DST	SW	0	
A	1953-1955	6	SST	SE	2	
AX	1963-1965	4	SST	SE	0	Retrievals in progress. Tanks AX-102 and AX-104 retrievals complete, AX-103 retrieval in progress, AX-101 retrieval scheduled to begin January 2023.
AY	1968-1970	2	DST	SE	1[a]	(Tank AY-102 retrieved, awaiting closure)
AW	1976-1980	6	DST	SE	0	
AZ	1970-1974	2	DST	SE	0	
AN	1977-1980	7	DST	SE	0	
AP	1982-1986	8	DST	SE	0	Feed tanks for DFLAW

Source: HNF-EP-0182, 2022, *Waste Tank Summary Report for Month Ending November 30, 2022*, Rev. 419, Washington River Protection Solutions, LLC, Richland, Washington.

[a] Tank AY-102 – Primary tank leak into the annulus.

DFLAW = direct-feed low-activity waste.
DST = double-shell tank.
NE = northeast.
NW = northwest.
SE = southeast.
SST = single-shell tank.
SW = southwest.

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[4] Four smaller tanks (200-series, ~55,000 gallons) were built along with the 12 larger tanks (100-series) in the initial tank farms (B, C, T, and U Farms). These small tanks are included in the tank counts.

The first known tank leak dated to the 1950s, with stress corrosion cracking along the weld lines indicated as the probable cause for most of the leaks identified (CNWRA-97-001).

Past Leak Mitigation Measures

Leak mitigation efforts at Hanford focused on removal of free supernatant liquid from the tanks. A campaign known as the Interim Stabilization Program was conducted to remove pumpable liquids, to reduce motive force and increase viscosity of the waste to reduce the risk of leaking. Criteria were established to be met for completing removal from the tanks.[5] To accomplish this campaign, a "well" was bored into the solids in the tank waste, and liquids were pumped from the well until as much liquid in the tank was removed as practical. This process was performed for all SSTs, not just the tanks known to be leaking. This process was deemed impractical for selected tanks; so instead, leak mitigation used additions of cement (Tank BY-105) or diatomaceous earth (Tanks BX-102, SX-113, TX-116, TX-117, TY-106, and U-104) to bind any free liquid in the tanks (LA-UR-96-3860, *Hanford Tank Chemical and Radionuclide Inventories: HDW Model Rev. 4*). The SSTs were then operationally isolated, with all transfer paths in and out of the tanks removed and blind flanged (sealed).

For the one known leak in a DST (Tank AY-102), the mitigation method was removal of the waste from the tank.

Risk and Impact of Tank Leaks

Single-Shell Tanks

Leak rates from SSTs have been minimized by removal or stabilization of free liquids (interim stabilization) in these tanks. However, these measures have not completely removed the potential for future leaks from residual liquids. Thus, continued storage of waste in these tanks has the potential to result in additional leaks of radionuclides and hazardous chemicals into the soil at the Hanford Site, and this risk increases as the tanks continue to age. This risk is known and captured in the programmatic risks for the RPP mission.

Retrieval operations to remove waste from a tank typically consist of sluicing the waste with water (or supernatant liquid from a DST) to dissolve salts and suspend solids, and then extracting the pumpable slurry. This process adds liquids back to the SSTs to mobilize the waste for transfer and could result in leakage of that added liquid from the tanks through existing leak locations. Methods to mobilize the waste without the addition of large amounts of liquid were demonstrated during C Farm retrievals, and methods to remove the waste using mining techniques that do not add water to the tank are currently being researched. This risk is known and captured in the programmatic risks for the RPP mission.

Thus, additional leaks from SSTs would add to the inventory of radionuclides and hazardous chemicals in the Hanford soil and groundwater plumes, but would have little programmatic impact on the tank waste immobilization program because (1) mitigation measures to minimize the risk of leaks from SSTs have been performed on all SSTs, (2) methods to retrieve the tanks have been developed to minimize leaks from retrieving the tanks and continued development of the tank retrieval methods is in progress, and (3) the SSTs are not used as part of the staging process for any other tanks (all SSTs are retrieved into a DST) and no material is transferred through a SST for transfer routing, thus no loss of programmatic function occurs.

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[5] The Interim Stabilization Program criteria were met if: (1) less than 50,000 gallons of drainable interstitial liquids remained; (2) 5,000 gallons of supernatant liquid remained; and (3) less than 0.05 gallons per minute of liquid flow if jet pumping was used. DOE successfully completed the Interim Stabilization Program in 2010.

Acceleration of the retrieval and immobilization process for the waste stored in SSTs would minimize the risk of additional leaks. Acceleration not only requires available DST space to receive the retrieved waste, but also requires a significant investment in tank farms infrastructure. The infrastructure investments include the equipment needed to sluice the waste from the tanks and the piping systems to transfer the sluiced waste to the DSTs. For SSTs that are remote from the DST farms, additional facilities to allow efficient reuse of the sluicing supernatant liquids and efficient transfer to the DSTs are needed.

Double-Shell Tanks

As discussed above, one DST has developed leaks, Tank AY-102. These leaks occurred on the tank bottom and required the entire contents of the tank to be transferred to mitigate the leak. The Tank AY-102 leak resulted in material in the annulus of the DST, with no release to the ground. Tank AY-102 had been identified as the feed tank for the WTP HLW Vitrification Facility, and extensive characterization of the waste in the tank had been conducted. The loss of this DST required the WTP project to rework the feed staging arrangements and the work performed to evaluate processing the assembled batch. In addition, the material in Tank AY-102 was transferred to the AP Farm and required adjustments to the operational plans for the AP Farm tanks.

While a leak in a DST would typically not result in a release to the soil since the leak would be captured by the secondary tank, the programmatic impact of a DST leak is much larger than a leak in an SST. Assuming the leak requires the tank to be emptied (similar to Tank AY-102), the leak results in loss of function of two DSTs (at least temporarily), with the leaking tank being unusable and the tank(s) that received the waste potentially being full. Depending on how the tanks were planned for use, the programmatic issue could be greater than just loss of storage space. For example, Tank AP-106 was designated as the tank to receive pretreated supernatant liquid from the TSCR system for staging feed to LAW vitrification during DFLAW processing. Since the tank contained unprocessed supernatant liquid, an extensive process was used to empty the tank to support DFLAW feed. A leak in Tank AP-106 would require a new DST to undergo the cleaning process, would delay the DFLAW program much longer than a leak in other DSTs, and would create additional waste from the cleaning process.

Failures of selected DSTs may have little to no impact on the overall immobilization program if the tank failure does not prevent continued operations with the other DSTs except for the loss of operational flexibility, as described above, and potential diversion of funds and resources that could impact removal and treatment schedules. As an example, the leak in Tank AY-102 has not resulted in delays to the immobilization program. Full support of expected WTP operations is expected from the tank farms even with the loss of the tank and as demonstrated by the current integrated flowsheet models, which take into account the loss of Tank AY-102. Failures of a tank with a dedicated function, such as Tank AP-106, could result in a 1- to 3-year delay to repurpose other tanks for that function.

As with the SSTs, acceleration of the RPP mission would reduce the risk of leaks developing in the DSTs prior to mission completion. Unlike the SSTs, the DSTs have a programmatic role in the overall RPP, and development of leaks in other tanks could require significant changes to the planned execution of the RPP. Note that the risk is recognized by the DOE Office of River Protection (ORP) and Hanford Site contractors and is part of the existing risk registers for tank waste treatment.

The failure of Tank AY-102 was attributed to pitting corrosion resulting from reactions with chemicals in the tank waste (Follett 2018). In response, ORP conducted an evaluation of the extent of condition and adopted measures to minimize the risk of similar leaks in the remaining DSTs.

Structural Failure

The risk of a structural collapse of a SST or DST tank during the mission, similar to the collapse of the plutonium-uranium extraction (PUREX) tunnel at Hanford, is not considered in this evaluation. As noted above, the Hanford Site has extensive surveillance programs for the waste tanks that should allow early detection of any structural issues and allow for mitigation measures to be taken if signs of imminent structural failure were noted. These inspection protocols were not in place for the PUREX tunnel. These surveillance programs are described in RPP-7574.

Structural integrity of the 149 SSTs was assessed in a 2015 evaluation (RPP-RPT-49994, *Summary Report for the Hanford Single-Shell Tank Structural Analysis of Record – Single-Shell Tank Integrity Project Analysis of Record*), while structural integrity of the DST system was assessed in 2016 (RPP-RPT-58441, *Double-Shell Tank System Integrity Assessment Report (DSTAR)*).

2.0 REGULATORY OVERVIEW

Section 3125 of NDAA21 calls for continued analysis of approaches for supplemental treatment of LAW as a follow-on to the analysis required by Section 3134 of NDAA17. Although the focus of the FFRDC follow-on report is technical, NDAA17 Section 3134 requested analysis of "compliance with applicable technical standards" with respect to the approaches for supplemental treatment of LAW evaluated by the FFRDC. Section 3134 of NDAA17 specifically references technical standards promulgated under the following federal statutes:

- *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA)
- *Solid Waste Disposal Act* (commonly referred to as the *Resource Conservation and Recovery Act of 1976* [RCRA])
- *Federal Water Pollution Control Act* (often referred to as the *Clean Water Act of 1972* [CWA])
- *Clean Air Act of 1972* (CAA).

In addition to the regulations listed above, the FFRDC team also examined regulatory requirements associated with the following:

- *Atomic Energy Act of 1954* (AEA), as amended, and thereunder, DOE O 435.1, *Radioactive Waste Management*, and DOE M 435.1-1, *Radioactive Waste Management Manual*
- *National Environmental Policy Act of 1969* (NEPA)
- *Hanford Federal Facility Agreement and Consent Order – Tri-Party Agreement* (TPA) (Ecology et al., 1989)
- Washington State RCRA regulations (e.g., *Washington Administrative Code* [WAC] 173-303, "Dangerous Waste Regulations").[6]

In addition, Tribal Nations have treaty rights, traditional use areas, and other interests at the Hanford Site that are addressed by DOE and Tribal Nations through government-to-government interactions, pursuant to DOE O 144.1, *Department of Energy American Indian Tribal Government Interactions and Policy*.

The FFRDC team analyzed the regulatory aspects of the Hanford supplemental LAW treatment and disposal approaches evaluated in this report. The team also reviewed regulatory information provided in the NDAA17 report (SRNL-RP-2018-00687),[7] and considered additional reports and publications related to Hanford supplemental treatment of LAW that became available following issuance of the previous analysis. These advances and remaining uncertainties are described in further detail in Volume II, Appendix A and Appendix E, respectively. The FFRDC team concluded that the AEA (including DOE O 435.1 and DOE M 435.1-1), the RCRA LDRs, and TPA provisions specifically relating to selection of supplemental treatment for LAW—and in particular their interpretation and implementation by regulators—have the greatest significance for differentiating and selecting among supplemental treatment approaches. Technical implementation of permitting requirements (e.g., under RCRA, CAA, CWA) is not a major differentiator among alternatives; however, it is an important part of the regulatory background. The U.S. Government Accountability Office (GAO) report GAO-22-104365, *Nuclear Waste Disposal: Actions Needed to Enable DOE Decision That Could Save Tens of Billions of Dollars*, on Hanford tank waste summarizes how each of these elements of the legal framework applies to Hanford LAW requiring supplemental treatment:

- ***Atomic Energy Act of 1954*, as amended**, authorizes DOE to regulate the radioactive component of mixed HLW.

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[6] Additional information is provided in Ecology 96-401, *Differences Between Washington State and Federal Rules--Highlights.*

[7] Regulatory issues addressed in SRNL-RP-2018-00687 (Section 2.5, page 30) are discussed in Volume II, Appendix I.

- ***Resource Conservation and Recovery Act of 1976*, as amended**, governs the treatment, storage, and disposal of the hazardous waste component of mixed waste. EPA has authorized the Washington State Department of Ecology (Ecology) to administer its own hazardous waste regulatory program in lieu of the federal program.
- **DOE O 435.1 and DOE M 435.1-1**, issued in July 1999 and subsequently revised, set forth procedures for the management of DOE's radioactive wastes in a manner that is protective of worker and public health and safety and the environment. Under the manual associated with this Order, DOE has two processes for determining that waste can be managed as non-HLW, which is less expensive to manage and dispose of than HLW.
- ***Hanford Federal Facility Agreement and Consent Order – Tri-Party Agreement* (TPA)** (Ecology et al., 1989) is an agreement among DOE, EPA, and Ecology that lays out, among other topics, a process and a series of legally enforceable milestones for selecting a technology and constructing facilities to treat the supplemental LAW.
- The **Consent Decree (2010), as amended**, was established as a result of litigation brought against DOE by Ecology for missing certain TPA milestones. This judicially enforceable Consent Decree establishes, among other items, specific cleanup milestones for retrieval of waste from certain specified tanks and the commissioning and operation of the WTP.

The FFRDC team did not draw conclusions as to the likelihood that any given approach for supplemental treatment would be acceptable to or approved by Ecology. Instead, the team viewed regulatory acceptance as an uncertainty, one that could be resolved in a number of different ways, including by negotiation, legislative or agency action, or judicial decision.

Management of the low-activity fraction of tank waste at different DOE facilities is accomplished under different regulatory frameworks. For example, at SRS, tank waste is treated, and the low-activity fraction is disposed of at the Saltstone Facility, which is regulated under the CWA, through a wastewater operating permit. As discussed below, Hanford tank waste is regulated under RCRA, and consequently the CWA permitting approach used at SRS is not applicable.

The assessment of the key regulatory issues presented by the LAW supplemental treatment approaches evaluated by the FFRDC team follows. Supplemental regulatory background and information are provided in Volume II, Appendix I.

Regulatory Challenges for Selection of a Non-Vitrification Approach for Supplemental Treatment of Hanford Low-Activity Waste

Ecology's position is that all Hanford tank waste, including LAW, that is intended for disposal at Hanford, is required to be vitrified or alternatively must obtain a variance under RCRA prior to disposal.[8] Ecology told the FFRDC team that compliant disposal of non-vitrified LAW from Hanford tanks could not take place anywhere on the Hanford Site or in the state.[9] However, with respect to out-of-state disposition of LAW, Ecology states that "grouting of tank waste may be appropriate depending on the disposal facility's geology and waste acceptance criteria" (Volume II, Appendix J).

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[8] Ecology notes that disposal (or treatment) of tank waste in any form onsite at Hanford would require Ecology's approval through the RCRA permitting process, with "significant public input from stakeholders and the impacted communities, including tribal nations." The FFRDC team provided questions to Ecology regarding Ecology's understanding of the legal and regulatory context for selection of supplemental LAW treatment capacity. Ecology provided a detailed response to the questions, which is provided in its entirety as Volume II, Appendix J.

[9] "Ecology notes that tank waste solidified into a grout matrix will not be able to meet waste acceptance criteria at any landfill disposal facility in the state of Washington, whether on or off the Hanford Site" (Volume II, Appendix J).

DOE conducted the initial phases of a DOE pilot research and development (R&D) program at Hanford, the Test Bed Initiative (TBI).[10] The TBI pilot included off-site commercial grout treatment and disposal at a licensed out-of-state commercial land disposal facility of a small quantity (3 gallons [11.4 L]) of tank waste that DOE has determined is not HLW under the AEA because the waste meets the criteria for waste incidental to reprocessing (WIR), pursuant to DOE O 435.1.[11] The LAW used in the 3-gallon TBI demonstration was grouted in Washington State at the Perma-Fix Northwest, Inc. (Perma-Fix Northwest) treatment facility, located near the Hanford Site, and was transported to and disposed of at the Waste Control Specialists, LLC commercial mixed waste disposal site in Andrews, Texas. Ecology has nonetheless expressed general concerns about the off-site disposition of Hanford tank waste. Of greatest concern is the prospect that non-vitrified waste deemed unacceptable for out-of-state disposal might be returned to or unable to be shipped from Hanford. Ecology's concern about "orphaned" tank waste also extends to any LAW that would be treated on the Hanford Site by a method other than vitrification (Volume II, Appendix J).

DOE asserts that vitrification is not required for LAW for which DOE determines the radioactive component is not HLW and not to be treated at WTP. Where, for example, DOE has made a WIR determination that the LAW used in the TBI demonstration is not HLW, the Department contends that it is lawful to use a non-vitrification treatment method, such as grout, either onsite at Hanford or at an off-site commercial treatment facility, and/or to dispose of the grouted LAW either onsite at the Hanford IDF or offsite at a commercial land disposal facility (GAO-22-104365).

Key legal instruments that address the issue of vitrification versus alternative treatment technologies for Hanford LAW include the TPA (Ecology et al., 1989), RCRA, the state's EPA-authorized RCRA program, AEA, and NEPA,[12] and other regulations, DOE Orders, and guidance under the foregoing.[13] The discussion that follows provides context and a brief overview of the key aspects of the regulations that may impact alternatives selection (additional discussion is provided in Volume II, Appendix I).

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[10] The 3-gallon TBI was conducted by DOE as a RCRA treatability study pursuant to WAC 173-303-071(3)(r) and (s): 40 CFR 261.4(e) and (f).

[11] Based on the positive results of the 3-gallon TBI, DOE and Ecology had begun planning for another TBI action, which would involve off-site grout treatment and out-of-state commercial land disposal with respect to another 2,000 gallons of Hanford tank waste that DOE determines to be WIR. DOE had submitted a request for a RCRA research, development, and demonstration (RD&D) permit to Ecology for the 2,000-gallon TBI; however, DOE subsequently rescinded its permit request. Accordingly, the 2,000-gallon TBI is no longer formally under consideration, although Ecology has indicated support for the 2,000-gallon TBI and that the permit process for the demonstration will restart (see Volume II, Appendix J).

[12] Although not discussed in detail in this report, NEPA is a federal statute that requires federal agencies to assess the environmental effects of their proposed actions prior to making decisions. NEPA has been a key part of the framework for decision-making on remediation at Hanford, including with respect to disposition of tank waste, in part through preparation of detailed analysis of tank waste alternatives in EISs (e.g., TC&WM EIS [DOE/EIS-0391]*)*. The TC&WM EIS specifically evaluates alternative supplemental treatment options for Hanford LAW, including both vitrification and non-vitrification alternatives.

[13] Additional laws and regulations relevant to supplemental treatment of LAW at Hanford, including the CWA, CAA, and NEPA, are discussed in Volume II, Appendix I.

Hanford Tri-Party Agreement

The Hanford TPA is a comprehensive cleanup agreement among DOE, Ecology, and EPA, who entered into it pursuant to (variously) CERCLA, RCRA, and the Washington Hazardous Waste Management Act.[14] The parties signed the TPA initially in 1989, and it is periodically updated based on negotiated changes to process and mission direction. Among other actions, the TPA requires that remediation of the Hanford tanks, including disposition of their contents, be conducted under RCRA, rather than CERCLA. Washington State, specifically Ecology, is the entity authorized by EPA to implement RCRA in the state, using the state's RCRA regulations in lieu of EPA's.[15] The TPA Action Plan establishes milestones for DOE completion of remediation tasks agreed to by the parties, including retrieval and disposition of tank wastes.[16] In addition to regulatory oversight by Ecology, implementation of TPA milestones for the Hanford tanks is being overseen by a federal district court in Washington State with continuing jurisdiction, pursuant to a Consent Decree.[17]

The TPA specifically mentions supplemental treatment of LAW in the Action Plan, which contains ambiguous milestones with respect LAW treatment. Milestone M-062-00 addresses pretreatment and vitrification of Hanford HLW and LAW. Milestone M-062-45, agreed to more recently, specifically addresses selection of *supplemental treatment* for LAW.

Milestone M-062-45 established a deadline for selection of a supplemental treatment method for LAW, considering supplemental treatment options including a second LAW vitrification facility.[18]

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[14] The TPA (Part One, Article III) states that the general purposes of the agreement are to:

"A. Ensure that the environmental impacts associated with past and present activities at the Hanford Site are thoroughly investigated and appropriate response action taken as necessary to protect the public health, welfare and the environment;
B. Provide a framework for permitting TSD [treatment, storage, and disposal] Units, promote an orderly, effective investigation and cleanup of contamination at the Hanford Site, and avoid litigation between the Parties;
C. Ensure compliance with RCRA and the *Washington Hazardous Waste Management Act* (HWMA) (Chapter 70A.300 RCW) for TSD Units including requirements covering permitting, compliance, closure, and post-closure care.
D. Establish a procedural framework and schedule for developing, prioritizing, implementing and monitoring appropriate response actions at the Hanford Site in accordance with CERCLA, the National Contingency Plan (NCP), 40 CFR 300, Superfund guidance and policy, RCRA, and RCRA guidance and policy;
E. Facilitate cooperation, exchange of information and the coordinated participation of the Parties in such actions; and
F. Minimize the duplication of analysis and documentation."

[15] TPA (2021) identifies Ecology as the lead regulatory agency for tank remediation and indicates that such remediation will be conducted under RCRA.

The TPA views remediation undertaken under either CERCLA or RCRA as satisfying the requirements of both statutes (see Ecology et al. [1989] Article VIII, Paragraph 17). Although cleanup under RCRA is regarded as equivalent to that undertaken under CERCLA, as a practical matter, there may be differences in decisional processes – and outcomes – depending on which statute governs the remedial action and which party is in the lead. For instance, CERCLA is implemented by EPA, with input from states and EPA implementation of more stringent state standards (including state RCRA standards) *if* EPA determines that such state standards are "applicable" or "relevant and appropriate." RCRA requirements including those for remediation, on the other hand, are implemented by states authorized by EPA to carry out those requirements, including Washington State, in accordance with such state requirements, which may be more stringent than and/or somewhat different from EPA's requirements. Remediation under RCRA is managed by the authorized state under its RCRA permit authority. Once a state is RCRA-authorized to implement a given set of RCRA requirements, such as permitting, EPA retains residual RCRA enforcement authority, but does not generally intervene in the state's implementation of the state-authorized portion of the RCRA program. EPA directly implements RCRA program requirements in states that lack authorization to implement those particular RCRA requirements and, as a practical matter, only rarely initiates enforcement of the federal RCRA regulations in an authorized state.

[16] The TPA Action Plan (TPA, 2022) establishes "the overall plan for hazardous waste permitting, meeting closure and post-closure requirements, and remedial action under RCRA and CERCLA and the Washington State Hazardous Waste Management Act." The Action Plan contains a work schedule (milestones) that sets priorities.

[17] Consent Decree (2010), as amended by Consent Decrees (2016a, 2016b, 2018, and 2022).

[18] Item 3 of Milestone M-062-45 requires "Supplemental treatment selection (a one-time selection to be made not later than April 30, 2015) and [negotiation of] milestones, which must be consistent with M-062-00 as established by M-062-45 item #5. A 2nd LAW Vitrification Facility must be considered as one of the options."

While M-062-00 addresses vitrification, M-062-45 introduces the possibility that a different supplemental treatment may be selected. DOE and Ecology do not agree on what is required – or allowed – under the TPA for supplemental treatment of LAW and are engaged in a dispute resolution process under Article VIII of the TPA to resolve the matter.[19] Independent of but parallel to the TPA selection process, Congress enacted NDAA17 Section 3134, and subsequently NDAA21 Section 3125, to help facilitate an informed decision selecting the approach for supplemental treatment for Hanford LAW. The NDAA provisions task the FFRDC with assessing supplemental treatment approaches for LAW—specifically including vitrification, FBSR, and grout—and with developing a decision framework for use by decision-makers in selecting among potential treatment approaches.

A decision on the supplemental LAW treatment alternative will require negotiation of additional milestones to be added to the TPA for any treatment alternative. The TPA provides a negotiation vehicle for issues such as supplemental LAW treatment selection. Agreements on approach and priorities made within the TPA framework are intended to establish a basis for permitting activities.

Determining RCRA Treatment Standards Applicable to Mixed Waste Destined for Land Disposal

The kind of supplemental treatment that is required—or allowed—for the Hanford LAW depends substantially on the requirements of, and the scope of regulatory authority and regulatory discretion under, both RCRA and the AEA with respect to mixed wastes. Hanford tank waste is "mixed waste" – a mixture of both chemically hazardous and radioactive waste, and as such is subject to both RCRA and the AEA. In Washington State, Ecology rather than EPA is in charge of implementing the RCRA program, including regulation of mixed waste, permitting of mixed waste treatment, storage and disposal facilities, and implementation of the LDR treatment standards (40 CFR 268, "Land Disposal Restrictions") for mixed waste, by incorporating by reference EPA's LDR program in WAC 173-303-140(2)(a).[20]

Among the key regulatory questions relevant to the issue of allowable supplemental LAW treatment under RCRA are: whether the Hanford LAW is mixed *HLW* for purposes of implementing the RCRA LDR regulations; and whether Ecology is authorized to determine that the RCRA LDR standard for mixed HLW applies to LAW when DOE has determined under the AEA that the radioactive portion[21] of the waste is not HLW, or in the absence of a DOE determination characterizing the radioactive portion of the mixed waste. As discussed below, DOE asserts that under the AEA it is DOE that is authorized to determine whether the radioactive portion of tank waste is HLW – or not-HLW. Ecology contends that, pursuant to its RCRA authority, it is authorized to determine that the tank waste qualifies as high-level mixed waste for purposes of the state's implementation of the RCRA LDR regulations (Volume II, Appendix J).

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[19] With the agreement of all parties, the TPA could be amended, for example, to clarify the intent with respect to supplemental treatment of LAW and/or to specify use of a particular supplemental treatment method for LAW at Hanford.

[20] Under RCRA, EPA can authorize a state to implement the RCRA program using its own regulations, provided the state's regulatory program is no less stringent than, consistent with, and equivalent to the federal RCRA program; state programs can be more stringent than the EPA program. EPA generally gives authorized states broad discretion to implement RCRA program requirements. However, in authorized states, EPA still retains RCRA enforcement authority that it may choose to exercise in appropriate instances.

[21] EPA refers to the radioactive constituents in the mixed waste as the "radioactive portion." DOE characterizes waste and makes a determination as to whether waste is HLW or not after completion of treatment pursuant to DOE O 435.1. At Hanford, the plan is to separate tank waste into a high-activity fraction and a low-activity fraction (i.e., LAW) for separate treatment and disposal. After waste fractions are physically separated and treated, the low-activity fraction of the tank waste may have a different classification (not HLW vs. HLW) than the high-activity fraction of the tank waste.

Mixed waste is dually regulated under both RCRA and the AEA. Under the dual regulatory scheme, EPA—or the RCRA-authorized state—regulates the chemically hazardous portion of mixed waste (only), and DOE regulates the radioactive component of mixed waste (only). EPA recognizes this AEA/RCRA jurisdictional divide, which stems from Section 11(e) of the AEA, RCRA Section 1006(a) and 10 CFR 962, "Byproduct Material." These provisions exempt the radioactive portion of mixed waste from regulation under RCRA.[22]

As EPA states with respect to mixed waste:

> "*RCRA regulates the hazardous waste portion of the [mixed] waste as any other hazardous waste, while the AEA regulates the RCRA-exempt radioactive portion.* If waste is categorized as "mixed waste," the handlers must comply with both AEA and RCRA statutes and regulations, which are usually compatible. In the cases where AEA and RCRA contradict each other, the provisions in Section 1006(a) of RCRA allow the AEA to take precedence over RCRA." [Emphasis added.] (EPA, 2022)

EPA's "Third-Third Rule," which establishes the LDR standards for mixed waste bearing waste numbers D001–D017, requires that specified non-wastewater high-level mixed waste, "Radioactive high-level wastes generated during the reprocessing of fuel rods," falling within D002 and D004-11, be treated by the HLVIT method prior to land disposal (40 CFR 268.40, "Treatment Standards for Hazardous Wastes"). Mixed wastes not meeting this description do not require vitrification, but must meet all LDR standards applicable to the waste. Where there is no specific treatment standard for radioactive mixed waste, the treatment standard for the hazardous waste (as designated by EPA waste code) applies (40 CFR 268.42(d)).[23]

The high-level mixed waste that EPA requires be treated by HLVIT, as specified in the Preamble to the Final Third-Third Rule, is: "*the high-level fraction* of the mixed waste generated during the reprocessing of fuel rods exhibiting the characteristics of corrosivity [D002] and toxicity for metals [D004-D011]" (55 FR 22627, "BDAT Treatment Standards for D001, D004, D005, D006, D007, D008, D009, D010, and D011"). The Preamble emphasizes that vitrification is only necessary for the "high-level fraction" of DOE "high-level waste generated from reprocessing of fuel rods." Following separation of "the low-level radioactive waste fractions from the high-level radioactive waste. *The high-level radioactive portion is then vitrified… By separating high-level and low-level mixed wastes, the amount of high-level waste that may require vitrification treatment can be reduced*" (55 FR 22627, "b. Applicable Technologies"). The Preamble also states that stabilization using grout is acceptable and anticipated treatment for the low-activity fraction of DOE high-level mixed waste. "The performance data indicate that [grout] stabilization provides immobilization of the characteristic metal constituents and radioactive contaminants for this low-level radioactive waste, and that it is possible to stabilize the RCRA hazardous portions to meet the treatment levels for the characteristic metals." The Preamble found a variety of different non-vitrification treatments suitable for treating organic chemicals in the low-activity fraction of DOE high-level mixed waste to meet LDR standards (55 FR 22626-27, "8. Radioactive Mixed Waste").

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[22] Section 11(e) of the AEA confers on DOE authority over "byproduct material." Byproduct material, which includes DOE radioactive waste, is excluded from the RCRA definition of solid waste, of which hazardous waste (including mixed waste) is a subcategory. Further, 10 CFR 962, interpreting the RCRA/AEA regulatory interface, defines as RCRA-exempt the radionuclides portion of mixed waste, in respect of mixed waste that DOE owns or produces at DOE facilities and self-regulates under the AEA (52 FR 15940, "Part 962—Byproduct Material"). Accordingly, the radioactive components of DOE's mixed waste are exempt from RCRA regulation and DOE, not EPA or authorized states, has the authority to regulate the radioactive portion of mixed waste at DOE facilities.

[23] Volume II, Appendix C discusses how specific alternatives have been designed to achieve applicable LDR standards. Note that the NDAA17 report (SRNL-RP-2018-00687, pages 265-266) addressed the possibility that pretreated LAW might potentially be recategorized as a wastewater under 40 CFR 262.11(a) and if so, according to the regulations in 40 CFR 268.40, would not be subject to the HLVIT LDR standard; the HLVIT standard only applies to non-wastewaters.

However, as similarly reported by GAO in December 2021, the FFRDC team found that Ecology and DOE are not in agreement about what kind of treatment is mandated—or acceptable—for Hanford LAW to comply with RCRA LDR regulations (GAO-22-104365). Ecology asserts that the state's LDR regulations (which largely mirror EPA's regulations) require *all* tank waste, including LAW, to be treated by the HLVIT method prior to land disposal at Hanford. The state contends that the HLVIT LDR standard "attached" to all tank wastes at Hanford in 1990 when EPA promulgated its LDR standards for mixed wastes.[24] Ecology believes that the HLVIT standard remains attached to the tank waste until the waste either meets the HLVIT standard or a variance has been granted, modifying (or waiving compliance with) the HLVIT standard (Volume II, Appendix J). DOE's view, however, is that – although LAW being processed through the WTP will be vitrified – LAW requiring supplemental treatment that DOE has determined is not HLW can lawfully be stabilized with grout to comply with the LDR requirements; this would include, for example, LAW for which DOE has made a WIR determination pursuant to the AEA under DOE O 435.1. Ecology disagrees, stating that "DOE's issuance of a final WIR Determination does not extinguish the RCRA LDR treatment standard of HLVIT" (Volume II, Appendix J).

Variances from RCRA Land Disposal Restrictions Standards

Variances from RCRA LDR standards such as HLVIT, if the LDR standard is applicable, are potentially available. Washington State's LDR regulations allow for a site-specific treatability variance from otherwise applicable LDR standards, which could be granted by Ecology. A site-specific treatability variance could also be approved by the regulatory authority in another state, if the state is authorized to grant treatability variances.[25] Ecology approved a site-specific treatability variance for Hanford tank waste in 2019. In that instance, Ecology approved a treatability variance sought by DOE for Hanford LAW expected to be processed in the WTP. To ensure compliance with the LDR standards, Ecology would have required sampling of the waste for organics – sampling that DOE believed might endanger workers. Instead of sampling, the approved site-specific treatability variance required vitrification of the waste to address the organics (Schleif, 2019).[26]

Another option for a variance from LDR standards would be to petition for a determination of equivalent treatment, allowing another method of supplemental treatment than vitrification for Hanford LAW. Alternatively, DOE could petition EPA for a national treatability variance allowing another method of supplemental treatment than vitrification for the Hanford LAW.

Disposal of a Non-Vitrified Low-Activity Waste Form in the Hanford Integrated Disposal Facility

Ecology opposes disposal of grouted LAW (as a primary waste form) onsite at the IDF. Ecology contends that, on account of Hanford's geology, disposal of grout-treated LAW in the IDF would cause exceedances of SDWA maximum contaminant levels for some tank waste constituents, potentially threatening groundwater and the Columbia River (Volume II, Appendix J).

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[24] Although the Third-Third rule was published in the Federal Register on June 1, 1990, with the treatment standards effective May 8, 1990, radioactive mixed waste was granted a 2-year national capacity variance until May 8, 1992 (40 CFR 268, Appendix VII, Table 1 – Effective Dates of Surface Disposed Wastes, footnote a).

[25] EPA guidance on use of site-specific treatability variances in cleanup indicates that such variances may be justified when properties of the waste at issue are different from properties of the waste on which the treatment standard was based or where the treatment standard was based on best demonstrated available technology that is inappropriate for the waste at issue. The guidance illustrates a number of circumstances encountered in cleanups where approval of such variances may be appropriate. These include, for example, cleanups where bench- or pilot-scale studies indicate that LDR treatment standards cannot be achieved; and sludges placed in surface impoundments prior to the effective date of LDR standards, which have changed composition due to prolonged exposure to natural conditions (Shapiro, 1997).

[26] The 2019 variance would not apply to supplemental LAW options for grout and FBSR evaluated in the NDAA21 follow-on report (this document) because the LAW would not be treated at the WTP.

Based on prior analyses, the FFRDC team believes that disposal of grouted LAW at the IDF may well meet applicable standards for groundwater (based on the performance evaluation in SRNL-RP-2018-00687, Appendix F), although, mitigation measures may be required if modeling projects that future groundwater concentrations may exceed 75% of the maximum contaminant limit for any of these constituents, under Ecology's implementation of RCRA (IDF Permit Condition III.11.I.5.a.ii [Ecology, 2021]). Currently, the permit for the IDF does not allow disposal of a grouted LAW as a primary waste form, although Ecology is in the process of amending the permit to authorize disposal of grouted secondary waste from vitrification of Hanford tank waste.[27]

Out-of-State Treatment and/or Disposal of Hanford Low-Activity Waste

At this time, no significant regulatory barriers under RCRA or the AEA appear to preclude the treatment and disposal of Hanford LAW at out-of-state commercial facilities.[28] Ecology implements the RCRA LDR regulations with respect to Hanford tank waste and for prospective treatment facilities offsite but located in Washington State through its permit authority (e.g., over RCRA facilities, including Perma-Fix Northwest).

Nothing in the RCRA regulations would appear to preclude treatment of mixed tank waste at an out-of-state commercial treatment facility and disposal at an out-of-state commercial disposal facility, provided the off-site facility is licensed to treat the tank waste, and the treated tank waste meets disposal facility waste acceptance criteria and LDR requirements prior to disposal. Off-site commercial treatment in Washington State (at Perma-Fix Northwest), followed by disposal at a commercial disposal facility (Waste Control Specialists in Andrews, Texas) of Hanford tank waste, was successfully accomplished during the 3-gallon (11.4 L) TBI demonstration. Further, if the tank waste coming from Hanford for off-site commercial disposal would not be expected to meet all applicable LDR standards, the out-of-state land disposal facility could petition EPA for a "no migration" variance allowing disposal of Hanford tank waste that does not meet LDR standards.[29]

Ecology is concerned, however, that unvitrified waste leaving the Hanford Site may yet return to Hanford and be "orphaned" there, if for some reason the receiving treatment or disposal facility or its host state find the waste unacceptable once the LAW arrives. Ecology indicates potential support for out-of-state treatment and disposal for as much as 500,000 gallons (1.9 million L) of tank waste that is determined to meet DOE M 435.1-1 WIR requirements under the TBI program, although this program has only dispositioned 3 gallons (11 L) of tank waste to date and is an R&D program separate from treatment of LAW. Ecology has indicated that enforceable agreements with potential off-site facilities will be required, guaranteeing that tank waste leaving the Hanford Site for treatment and/or disposal elsewhere will not be returned to the Hanford Site. DOE could seek to address those concerns through technical approaches such as using a LAW treatment methodology, preceded by sampling and analysis, where waste would not be immobilized by grout unless the resulting immobilized waste would meet the waste acceptance criteria of the receiving facility. Having more than one option for out-of-state disposal would mitigate issues of access to off-site waste treatment and/or permanent disposal facilities.

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[27] Grouted secondary waste would be disposed of in the IDF if such disposal is approved by Ecology. By contrast, grouted tank LAW would represent a far larger quantity than secondary waste if grouted waste were approved to be disposed of there.

[28] Treatment and disposal of tank waste offsite or out-of-state would involve some mode of transportation of the waste to the treatment or disposal facility. Transportation regulatory issues are addressed in Volume II, Appendix H.

[29] To obtain a no-migration variance, the land disposal facility would need to demonstrate that there will be no migration of hazardous constituents from the land disposal unit for as long as the waste remains hazardous. Although this is a difficult standard to meet, a number of no migration variances have been granted. In EPA (2021), EPA Region 7 proposed to reissue a "no migration" variance that the Agency had originally approved in 1990 for five underground injection well land disposal units. DOE's Waste Isolation Pilot Plant in New Mexico was also granted a conditional no migration variance by EPA; later-enacted Congressional legislation exempted the Waste Isolation Pilot Plant from the RCRA LDR requirements. The majority of no migration variances have been approved for underground injection wells (EPA530-K-05-013, *Introduction to Land Disposal Restrictions [40 CFR Part 268]*).

3.0 ANALYSIS METHODOLOGY

3.1 Current State of Technology

Vitrification and grouting are mature process technologies that have been operated at scale and that could be adapted to the specific design conditions for Hanford LAW. FBSR would effectively be a first-of-a kind facility with respect to the Hanford process configuration, waste characteristics, and scale, though its design and implementation would presumably be informed by experience with the Integrated Waste Treatment Unit facility currently being commissioned at INL that uses a different FBSR configuration.

The FFRDC team examined past and current results of experimentation regarding all three primary technologies, including both recent findings regarding immobilization fractions for iodine in glass and grout formulation, and pretreatment technology developments since the NDAA17 report (SRNL-RP-2018-00687). The team also examined pretreatment options for grouting, which include techniques for strontium-90 (^{90}Sr) removal and treatment of organic compounds. While this work is ongoing, the confidence that grout can safely be used to disposition LAW is higher now than it was at the time of the initial study. These advances and remaining uncertainties are described in more detail in Volume II, Appendix A and Appendix E, respectively.

3.2 Alternatives Development

Implementation of any of the three primary treatment technologies will require a sequence of process steps, including waste retrieval, interim storage, pretreatment to facilitate compatibility with the selected primary treatment process, air pollution control processes, disposal of the primary waste form, and treatment and disposal of solid and liquid secondary wastes. Alternatives were developed with a technical basis supporting the ability to meet necessary performance requirements as defined by federal regulatory requirements for implementation of RCRA, DOE requirements under DOE O 435.1, and NRC permitting requirements for MLLW disposal offsite, when applicable. Each treatment alternative consists of “building blocks” designed or selected to achieve each necessary process required in conjunction with the primary treatment technology to achieve a complete alternative that can comply with applicable regulations. All projects are assumed to be designed in compliance with applicable DOE Orders and requirements. The primary building blocks are:

- **Storage** of retrieved waste either in existing DSTs or new facilities
- **Pretreatment** consisting of one or more of (1) tank side cesium (and strontium) removal (TSCR), (2) ^{99}Tc removal, (3) ^{129}I removal, and (4) LDR organic chemicals destruction or removal
- **Primary treatment** consisting of either (1) vitrification, (2) FBSR, or (3) grouting
- **Primary disposal** consisting of either (1) onsite at the IDF or a new disposal unit, or (2) off-site disposal at a state or NRC-licensed MLLW facility (e.g., Energy*Solutions* [Clive, Utah] or Waste Control Specialists [Andrews, Texas])
- **Secondary waste treatment and disposal**.

Individual building blocks may be implemented at different locations (e.g., near-tank, on-site remote from the waste tanks, or offsite) and incrementally in time. Individual building blocks are summarized in Section 3.3 and further described in Volume II, Appendix C. The assumptions used as a basis for the alternatives are also included in Volume II, Appendix C.

The FFRDC team developed and evaluated 23 initial alternatives for supplemental treatment of LAW, four of which are described in Section 3.3, with all of the alternatives detailed in Volume II, Appendix C.

As specified in NDAA21, the alternatives included the three primary treatment technologies from the NDAA17 analysis (vitrification, FBSR, and grouting), with emphasis on advancing the details of the grout alternatives. A prescreening review narrowed the set of viable alternatives to 15 alternatives for detailed analysis. Subsequent assessment of the decision criteria defined in Section 4.0 showed that some alternatives employing a given primary treatment technology were "dominated" by other alternatives using the same technology. An alternative is said to be dominated if there is another alternative that scores at least as well on every decision criterion, and better on at least one (Kahneman, and Tversky, 1986). The assessment process is described in Section 4.1, and the detailed taxonomy is included in Volume I, Appendix A. The detailed analyses of the 15 alternatives are provided in Volume II, Appendix D. Some alternatives were not fully evaluated for reasons that are explained at the end of the corresponding descriptions in Volume II, Appendix C.

Once the assessments were complete, the FFRDC team selected for detailed comparison the most promising alternatives using each primary technology. With two exceptions, these were simply the undominated alternatives within that technology group.[30] These four alternatives illustrate the available performance and implementation trade-offs across and within technologies. The four selected alternatives are:

- Vitrification with on-site disposal at Hanford (Vitrification 1)
- FBSR solid monolith product with on-site disposal at Hanford (FBSR 1A)
- Grouting performed by an off-site vendor with off-site disposal (Grout 4B)
- Initial off-site grouting and disposal, followed by on-site grouting and disposal in containers (Grout 6).

Detailed implementation and LAW treatment schedules and cost bases were developed for each of the four selected alternatives (Volume II, Appendix F), assuming an annual DOE ORP benchmark budget for supplemental LAW treatment activities of $450 million in 2023 dollars. Because the NDAA21 Section 3125 did not provide budget guidance, this benchmark was selected based on comparability to the DFLAW budget.[31] The FFRDC team also assessed the robustness of its findings by performing sensitivity analysis against the precise budget level selected, future escalation rates, and the cost estimate ranges, including a completely unconstrained case. The results of this sensitivity analysis are provided in Volume II, Appendix F.

Each of the alternatives is assumed to operate in parallel with the WTP LAW Vitrification Facility, providing flexibility as to which specific tank wastes would be treated by WTP LAW vitrification or by the supplemental LAW treatment process. Out-of-state disposal was considered because the geology and expected performance of the off-site disposal facilities are different from those of the on-site disposal facility/site and offer an alternative disposal path for waste forms that may be deemed to be less suitable for on-site disposal. The FFRDC team based the analysis on the Hanford IDF and the commercial disposal sites in Clive, Utah, and Andrews, Texas.

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[30] The two exceptions were alternatives Grout 1A and FBSR 1B. Grout 1A had the lowest discounted lifecycle costs among all alternatives, and was thus undominated, but scored significantly lower than other grout alternatives in both long-term performance and implementation schedule. In the judgment of the FFRDC team, the cost savings were not sufficient to make Grout 1A a highly attractive option, compared to the other undominated grout alternatives. FBSR 1B, on the other hand, was eliminated on practical grounds; while FBSR 1B scored significantly higher than FBSR 1A in estimated long-term performance, this was driven entirely by the use of off-site disposal. When off-site disposal is available, all of the off-site grouting alternatives dominate FBSR 1B in performance and risk, at much lower lifecycle cost. FBSR 1B is thus not a reasonable candidate for selection, leaving FBSR 1A as the best candidate using FBSR technology. The full set of decision criteria assessed is presented in Section 4.1.

[31] The benchmark budget was assumed available starting in 2025 and full carryover of funds was allowed. The analysis showed that all alternatives, except Vitrification 1, could be completed within the $450 million (constant fiscal year [FY] 2023 dollars) annual allowance. For Vitrification 1, a budget of $555 million would allow for construction and operations (assuming full carryover) with the operations start date of 2050. A sensitivity analysis was also conducted with the results provided in Volume II, Appendix F, Section F.2.2, with summary Table F-4.

Disposal of secondary waste was considered for each alternative. Unless the immobilization step was performed offsite, the secondary solid waste was assumed to be disposed of onsite with the exception of alternatives that considered ^{99}Tc and ^{129}I removal. In those alternatives (Grout 1C and 2C), the immobilized secondary waste containing the ^{99}Tc and ^{129}I was assumed to be disposed of offsite. Additional information is provided in Volume II, Appendix C. For each vitrification and FBSR alternative, the secondary waste could be disposed of offsite, although off-site disposal does not result in any significant change in the rankings of the alternatives for these two technologies.

3.3 Alternative Descriptions

The alternatives for supplemental treatment and immobilization of LAW are divided into three technologies: vitrification, steam reforming, and grouting. This description provides an overview of the four selected alternatives identified in this report, along with their assumptions and schematics depicting the building blocks of the simple flowsheet. The four alternatives were selected to best illustrate the three technologies and the differences among them.

All of the alternatives that were fully evaluated in this report are shown in Table 3.3-1. Vitrification and FBSR (Vitrification 1 and FBSR 1A) were assumed to result in on-site (IDF) disposal of the primary waste form. The two grout alternatives have either all off-site (Grout 4B) or a mix of off-site and on-site disposal (Grout 6) of the immobilized waste form. All alternatives include continued operation of the LAW melters in the WTP for the duration of the mission. In alternatives where waste is found to be incompatible with the immobilization method, that waste is diverted to the WTP LAW melters. More detail is provided in Volume II, Appendix C.

Table 3.3-1. Title and Description of Alternatives

Alternative designation	Alternative title	Brief description
Selected Alternatives by Technology		
Vitrification 1	Single Vitrification Plant	Construct additional melter facility; glass disposal in IDF
FBSR 1A	Fluidized Bed Steam Reforming – On-site Disposal	Construct FBSR facility; dispose monolith waste form onsite
Grout 4B	Off-site Vendor for Grouting – Off-site Disposal	Ship liquid to off-site vendor for grouting; dispose containerized grout offsite
Grout 6	Phased Off-site and On-site Grouting in Containers	Phased approach of off-site vendor grouting and off-site disposal, followed by on-site grouting and on-site disposal
Other Evaluated Alternatives		
FBSR 1B	Fluidized Bed Steam Reforming – Off-site Disposal	Construct FBSR facility; dispose granular waste form offsite
Grout 1A	Single Grout plant – On-site Disposal	Construct single grout plant in 200 East Area; dispose containerized grout in IDF
Grout 1B	Single Grout plant – Off-site Disposal	Construct single grout plant in 200 East Area; dispose containerized grout offsite
Grout 2A	Separate Grout Plants for 200 East and West Areas – On-site Disposal	Construct grout plants in 200 East and West Areas; dispose containerized grout in IDF
Grout 2B	Separate Grout Plants for 200 East and West Areas – On-site Disposal	Construct grout plants in 200 East and West Areas; dispose containerized grout offsite
Grout 4A	Off-site Vendor for Grouting – On-site Disposal	Ship liquid to off-site vendor for grouting; dispose containerized grout in IDF

Table 3.3-1. Title and Description of Alternatives

Alternative designation	Alternative title	Brief description
Grout 5A	Single Grout Plant – On-site Monolith in Vault Disposal	Construct single grout plant in 200 East Area; dispose a monolith of grout in vaults
Grout 5B	Single Grout Plant – On-site Containers in Vault Disposal	Construct single grout plant in 200 East Area; dispose containerized grout in vaults
Grout 1C	Single Grout Plant with Technetium/Iodine Removal and On-site Disposal	Remove ^{99}Tc and ^{129}I, followed by Grout 1A
Grout 2C	Separate Grout Plants for 200 East and West Areas with Technetium/Iodine Removal with On-site Disposal	Remove ^{99}Tc and ^{129}I, followed by Grout 2A
Grout 1D	Single Grout Plant with Technetium/Iodine Sample-and-Send with Off-site/On-site Disposal	Analyze LAW; grout all LAW; select on-site or off-site disposal of container based on ^{99}Tc and ^{129}I content

^{99}Tc = technetium-99.
^{129}I = iodine-129.
FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.

The alternatives were formulated based on the prior work documented in the NDAA17 report (SRNL-RP-2018-00687) and expanded to include other versions of those alternatives as conceived by team members or drawn from recently developed concepts. Only immobilization methods that are of relatively high technical maturity and had (1) been demonstrated with comparable tank waste elsewhere at laboratory scale or larger, (2) been demonstrated at large scale with radioactive streams albeit with different waste feed compositions, and (3) evidence that they could pass the basic criteria, such as meeting RCRA criteria for hazardous metals, were considered. Assessment results and comparative analysis of all 15 evaluated alternatives are summarized in Sections 4.2 and 4.3, along with additional summary analysis of the four selected alternatives. More detailed comparisons of the four alternatives are provided in Volume I, Appendix B.

To illustrate the difference in cost magnitude between vitrification and grouting options, WRPS performed TOPSim model simulations to estimate the annual costs of construction and operations for an alternative similar to Vitrification 1 and an alternative similar to Grout 4B – referred to here as "Vitrification 1 (modified)" and "Grout 4B Early Off-site Disposition". Those model runs cover the entire Hanford tank waste mission (HLW, LAW, plus LAW supplemental treatment) (Table 3.3-2).

Table 3.3-2. TOPSim Hanford Tank Waste Mission Analyses

Simulation designation	Mission analysis title	Brief description
Vitrification 1 (modified)	Single Vitrification Plant – Modified (MR-50638[a])	Construct additional melter facility – 2050 start
Grout 4B (early off-site disposition)	Off-site Vendor for Grouting – Off-site Disposal (MR-50713[b])	Ship liquid to off-site vendor for grouting; dispose containerized grout offsite

[a] MR-50638, 2021, *Analysis of Alternatives (AoA) Scenario Alternative 18 Phased Startup*, Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.

[b] MR-50713, 2022, *NDAA LAWST Modeling Study*, Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.

Pretreatment

All LAW will be pretreated to remove ^{137}Cs equivalent to or less than the WTP LAW Vitrification Facility acceptance criteria (<3.18E-5 Ci/mole Na^+ [PNNL-28958, *Cesium Ion Exchange Testing Using a Three-Column System with Crystalline Silicotitanate and Hanford Tank Waste 241-AP-107*]), which is sufficient to permit contact-handled maintenance in all subsequent processes. In all alternatives, the liquid tank waste is assumed to be processed through the Tank Farms Pretreatment (TFPT) process or a similar system(s). Pretreatment in WTP does not preclude any alternatives but may impact the final waste classification. All wastes would be sampled and analyzed or otherwise verified to be compatible with downstream pretreatment and the immobilization method prior to processing.

The TFPT, described in the System Plan (ORP-11242, Rev. 9), is similar to the TSCR system. Using TFPT primarily removes ^{137}Cs, and also removes soluble ^{90}Sr and some actinides as an added benefit of using CST.[32] Use of TFPT and its removal of ^{137}Cs, ^{90}Sr, and some actinides is included for all alternatives. Conversely, pretreatment in WTP does not remove soluble ^{90}Sr, which would result in a larger portion of the liquid waste being Class B, limiting off-site LAW disposal of that portion to only Waste Control Specialists (Texas) if disposed offsite. The modeling for the System Plan (Rev. 9, Scenario 1B) indicates 750 IX columns (i.e., TSCR-size IXC-150s) of CST would be needed to pretreat all of the LAW, and the modeling done for this report indicates ~1,000 IX columns would be needed. Neither of these model runs was optimized, so the range of 750-1,000 IX columns is assumed. Vitrification of the spent CST is the assumed disposition path. Vitrification of 1,000 IX columns of spent CST is equivalent to 2.7 wt% of CST in the HLW glass, well within the demonstrated range of 10 wt% with sludge. The CST essentially substitutes for some of the glass formers used with HLW, so no impact on the quantity of glass produced is projected. All alternative estimates include an equal cost for 1,000 IX columns and a small modular system to sluice the CST out of the IX columns.

The simplified schematic of the TFPT process is shown in Figure 3.3-1. The schematic shows a filter followed by three CST IX columns in series, although the number of columns in series may change, depending on processing needs. The unprocessed tank waste is adjusted in the DST to the target sodium ion concentration, processed through the TFPT, and the decontaminated liquid is stored in an interim storage tank prior to immobilization in the supplemental LAW treatment process. The spent CST IX columns from TFPT are interim-stored onsite, with the expectation that the media will eventually be vitrified at the WTP HLW Vitrification Facility.

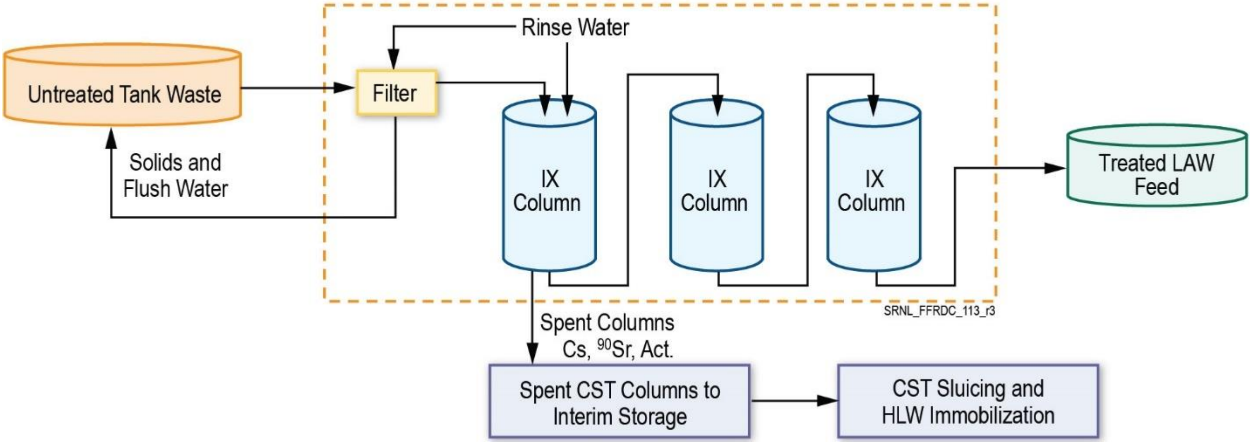

Figure 3.3-1. Tank Farms Pretreatment Process

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[32] CST is used as a common descriptor of the engineered bead form of the media produced by Honeywell UOP of Des Plaines, Illinois, and is designated as Ionsiv™ 9120-B or 9140-B.

The extent of removal of soluble ^{90}Sr and actinides by CST is not known for all feed stream compositions but is estimated to be 99% and 30%, respectively, unless the waste is a complexant waste. The estimate for non-complexant waste is based on limited testing of processing Tanks AW-102, AP-107, and AP-105 through IX columns of CST (PNNL-28783, PNNL-27706, and PNNL-30712). These tanks contain blends of supernatant liquid from several tanks and are expected to be representative of the strontium chemistry in non-complexant wastes. The ability of CST to remove strontium has been known since its invention (Zheng, 1996), and its absorption is included in the computer model (ZAM) developed by its inventors. Complexant waste could contain high soluble ^{90}Sr and actinides that may or may not be removed by CST. The $SrOH^+$ ion is the species known to be removed by CST (Zheng, 1996), and this may not be a dominant form in complexant waste.

The distribution coefficient for non-complexed ^{90}Sr is approximately 10 times greater than for cesium on CST media and is expected to produce waste that is less than NRC Class A low-level limits (1 Ci/m^3). The NDAA17 report (SRNL-RP-2018-00687) indicated that 90% of waste would reach Class A if 99% of the soluble ^{90}Sr was removed. The assumed pretreatment with TSCR/TFPT IX columns to remove ^{137}Cs also results in removal of 99% of soluble ^{90}Sr from non-complexant LAW. Removing ^{90}Sr from the non-complexant LAW is not a requirement. The benefit of creating a Class A waste form is that it increases the off-site disposal options for non-complexant LAW. Only two tanks are believed to contain complexant waste, and the planned treatment involves a separate strontium/transuranic (TRU) removal process (RPP-PLAN-51288, *Development Test Plan for Sr/TRU Precipitation Process*). That Sr/TRU Precipitation Process, along with CST treatment, is likely to result in a Class B waste, limiting off-site disposal to only Waste Control Specialists (Texas), if disposed offsite.

After TFPT, the liquid will be evaporated to remove excess water; with many of the organic species in the waste expected to partition to the condensate during that evaporation (a separate evaporator is not included for vitrification[33]). Many of the LDR organic compounds suspected to be in the waste would likely be removed to concentrations below the treatment standard by the evaporation process, as documented in:

- RPP-RPT-63493, *Tank Waste LDR Organics Data Summary for Sample-and-Send*
- RPP-RPT-64064, *Distribution of LDR Organic Compounds in Hanford Tanks Waste and the Implications to LAW Treatment by Cementitious Solidification/Stabilization*
- SRNL-STI-2020-00582, *Hanford Supplemental Low Activity Waste Simulant Evaporation Testing for Removal of Organics*
- SRNL-STI-2021-00453, *Potential for Evaporation and In Situ Reaction of Organic Compounds in Hanford Supplemental LAW*
- SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*.

The aqueous condensate containing the dissolved organics from the evaporator would be sent to the ETF since it is essentially identical to the condensate from the 242-A Evaporator that is currently dispositioned in the ETF. The ETF is equipped and permitted to destroy the tank-originated organics in the 242-A Evaporator aqueous condensate stream.

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[33] Evaporation for the LAW supplemental vitrification system is assumed in System Plan, Scenario 1B (ORP-11242, Rev. 9).

3.3.1 Alternative Vitrification 1, Single Supplemental Low-Activity Waste Vitrification Plant

The Vitrification 1 alternative considered in this assessment is shown in Figure 3.3-2. Disposal of the glass waste is assumed to be in the IDF in stainless steel containers. This scenario is comparable to the vitrification in the WTP LAW melter system and was included in the previous NDAA17 report (SRNL-RP-2018-00687). Because of the annual funding benchmark assumption for supplemental LAW treatment activities and the long construction time, this alternative does not begin radioactive operation until approximately 2050, which exacerbates the need for a larger facility to keep up with the HLW mission that starts in 2033. Based on information available at this time, meeting the HLW production mission schedule requires ~three times higher throughput than the current LAW melter facility to achieve the throughput needed, which corresponds to at least six LAW-sized melters. The cost for this additional melter facility increases by ~three times due to the larger facility with more melters (but cost is then discounted by 40% compared to the LAW melter facility to account for scale-up and increased design and construction efficiency).

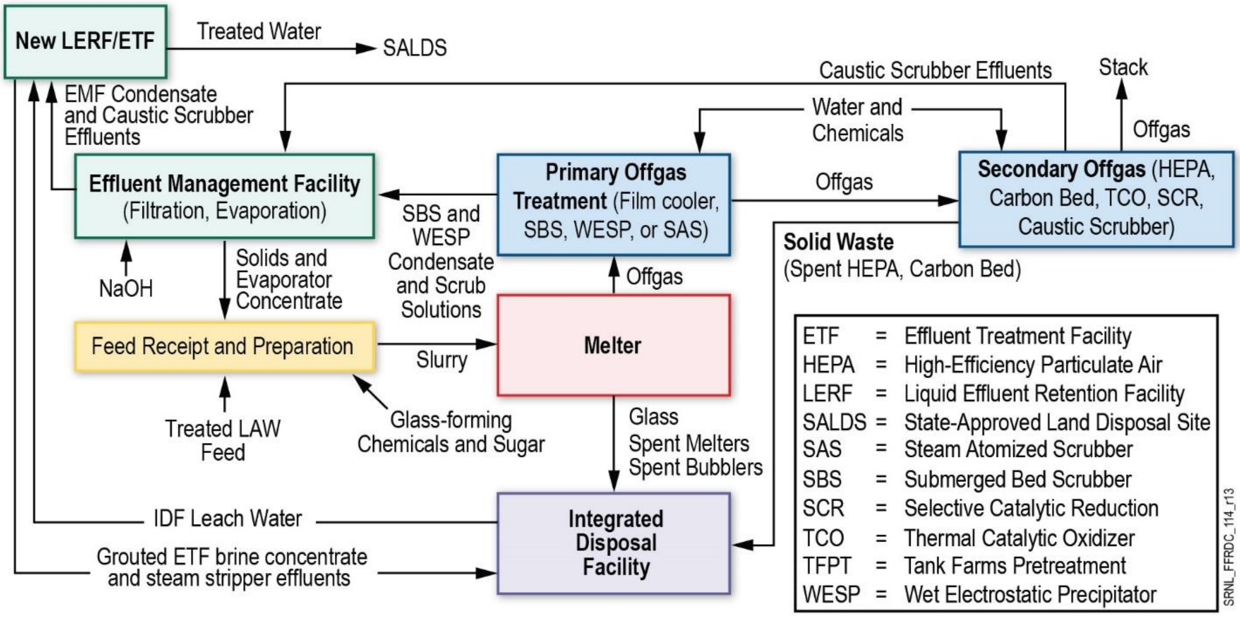

Figure 3.3-2. Flow Diagram of Vitrification

In this alternative, the existing DST system is assumed to be used to blend and stage the feed. The waste is assumed to be sampled in the DST and analyzed and found to be compliant with the pretreatment system to produce an acceptable glass waste form.

Waste vitrification technology consists of mixing a chemically characterized, aqueous waste stream with sugar, specific metal oxides, and metal carbonates to produce a slurry that is fed to a melter in which the slurry is incorporated into the melt pool. The melter is continuously bubbled by forcing air through submerged pipes in the molten pool to increase the melt rate. The volatile components are driven into offgas by heat, requiring a complex offgas system to treat the melter offgas prior to discharge and generating two secondary liquid waste streams and a solid secondary waste that also requires treatment. All water is vaporized into the offgas system, which typically has scrubbers and a condensate system that generates a liquid waste that is larger in volume than the original stream. Sulfate ion in the waste is one of the most challenging species because it has low solubility in the glass and can limit the waste loading.

The nitrates and nitrite salts are converted to ammonia, N_2, and NO_x by reaction with a reductant, such as sugar. The NO_x not captured in the primary offgas system is mostly converted to nitrogen in a catalytic reactor by reaction with added ammonia before the vapors are release to the atmosphere. A caustic scrubber further reduces the NO_x from the exhaust prior to release from the stack.

Organic chemicals present in the waste are mostly destroyed by the heat of the melter, but some others can be produced by incomplete reaction of the sugar. The mercury, ^{99}Tc, and ^{129}I are largely vaporized in the melter and collect in the offgas system. In the current WTP LAW Vitrification Facility, the offgas condensates are evaporated and recycled in an attempt to increase retention of the ^{99}Tc and ^{129}I in the glass.

Vitrification technology has been used in the U.S. and other countries to treat HLW, which is generally made up of a dilute aqueous salt solution slurry containing metal hydroxide and oxides, not a concentrated aqueous salt solution. The waste components are chemically bonded as part of the glass waste form; the interaction of the waste components with the glass-forming chemicals defines the amount of waste that can be immobilized in glass. The concentration and interaction among these components define the glass properties, such as durability. For LAW and supplemental LAW treatment, the Glass Shell v3.0 (a collection of proprietary models) is used to constrain the composition and loading of LAW glasses to control the sulfur tolerance of the melter feed to durability response, viscosity, and refractory corrosion. The final properties and composition of the vitrified waste form vary, but the models ensure that all the properties remain within acceptable processing and performance regions. The vitrified waste is poured using lifts into stainless steel containers. The containers, filled to at least 90%, are cooled, sealed, and decontaminated, and are stored temporarily prior to IDF disposal.

Glass waste loading is typically 10–25% (defined as waste sodium ion loading). The primary waste volume is reduced versus the aqueous waste, with the glass volume equivalent to ~40–50% of the liquid feed volume. The glass produced is a borosilicate glass with silica as the primary glass forming additive. Commercially produced borosilicate glass typically consists of silica, boron, aluminum, and alkali oxides, but additional glass species are present in the LAW glass as either contaminants in the waste feed (e.g., sulfur) or additives in the glass-forming chemical recipe to allow increased waste loading (e.g., tin and vanadium). Several different glass models have been developed for the expected glass waste forms to be produced during WTP LAW Vitrification Facility operations; these same models or improved versions would be expected to be used during LAW supplemental treatment operations. During processing, the composition of the feed is expected to be used to tailor a glass-forming chemical recipe that is optimized for each melter feed batch to allow the highest possible waste loading for that batch, while meeting all constraints for glass durability, conductivity, corrosion potential, density, viscosity, liquidus, and solubility limits for each species with limited solubility in glass (e.g., chromium, sulfur, selected noble metals).

When the existing LAW facility begins operations, the glass models developed in 2009 (ORP-56321, *Preliminary ILAW Formulation Algorithm Description: 24590-LAW-RPT-RT-04-0003, Rev. 1*) are expected to be used. The 2009 model has been translated into the immobilized LAW algorithm for facility use. Additional glass models have been developed that can improve the waste loading of LAW glass (PNNL-25835, *2016 Update of Hanford Glass Property Models and Constraints for Use in Estimating the Glass Mass to Be Produced at Hanford by Implementing Current Enhanced Glass Formulation Efforts*). These models are expected to be implemented once the LAW Vitrification Facility completes the commissioning process. The updated models are incorporated in the flowsheet modeling that developed the estimates for the feed to LAW supplemental treatment; therefore, the impact of the improved models is included in this analysis. The improved models have not been translated into an algorithm for use by the facility in a similar manner to the 2009 model. The feed rate, bubbling rate, and melter power are balanced in an attempt to maintain a cold cap on the melt pool. Melter offgas condensate consists of components that are volatile and semi-volatile at melter temperatures and any solids entrained into the melter offgas system. In the absence of a cold cap or during operation with a reduced cold cap, these species vaporize more completely.

All water fed to the system and the water added during primary offgas treatment processes becomes liquid secondary waste. The liquid secondary waste generated during vitrification is collected and processed through the EMF, which is expanded in this alternative to accommodate the additional volume from more melters.

This waste is collected and processed using filtration and evaporation in the EMF. The EMF evaporator bottoms are recycled to the LAW facility melter for retreatment so that the radioactive and hazardous components, such as ^{99}Tc, are forced into the glass at higher concentrations than a single-pass system would achieve.

The EMF overhead condensate and secondary offgas system liquids are transferred to the LERF/ETF for collection and further treatment. A new facility would likely be required for treatment of the supplemental LAW effluent, due to capacity limits of the current facility. Treated water from ETF is disposed of at a state-approved land disposal site (SALDS). After treatment in ETF, the concentrated brine waste from ETF is primarily an aqueous solution of ammonium and sodium sulfates. The brine concentrate stream will either be routed to the thin film dryer and made into a powder form or sent offsite to be grouted. Both waste forms will be sent to the IDF for disposal. As documented in RPP-RPT-60974, *ETF New Waste Stream Acceptance Package for WTP Effluent Management Facility*, this stream was determined to be suitable for acceptance at LERF/ETF under Revision 11 of the waste acceptance criteria (HNF-3172, *Liquid Waste Processing Facilities Waste Acceptance Criteria*). HNF-3172 has since been revised (Revision 12) due to the ETF documented safety analysis, and the WTP EMF waste stream evaluation will need to be performed again.

Solid secondary waste from the vitrification facility (e.g., high-efficiency particulate air [HEPA] filters, carbon bed media, bubblers) were assumed to be placed in a container, encapsulated in grout, and disposed of in the IDF along with the immobilized waste from the ETF. However, waste disposition will be an evolving process and efficiencies will be looked at after DFLAW operations commence.

3.3.2 Alternative FBSR 1A, Fluidized Bed Steam Reforming On-site Disposal

The FBSR process was described in the previous NDAA17 report (SRNL-RP-2018-00687). FBSR can convert radioactive liquid waste to a dry, granular mineral product. With proper controls, the mineral product consists of chemical structures that can retain the radionuclides and most other constituents of concern. FBSR has been researched, developed, and used commercially for over two decades for processing low-level radioactive wastes, but those applications are unlike the high sodium ion content, alkaline Hanford tank waste.

FBSR operates at temperatures up to 725–750°C to evaporate water in the waste, destroy organics and nitrates – converting them to carbon dioxide, nitrogen, water, and residual NO_x, and convert the solid residue into a leach-resistant waste form. Coal and oxygen are fed into the ceramic-lined vessel known as the denitration and mineralizing reformer (DMR) where they react in the presence of high temperature steam (500–600°C) to produce hydrogen and other reactive gas species.

The DMR contains a bed of particles that are the right size and density to be continually fluidized by steam that flows upward through the bed. The liquid tank waste is mixed with clay, and the slurry is sprayed into the bottom of the vessel. The remaining dissolved and undissolved components of the supplemental LAW (e.g., sodium, aluminum, halogens, sulfur, hazardous metals, and radionuclides, if present) react with the clay that is premixed with the waste feed to form the desired mineralized waste form. This product includes mineral structures of nepheline, carnegieite, sodalite, or nosean. These structures can incorporate the nonvolatile and semi-volatile elements in the waste feed either into the nepheline or carnegieite mineral structures or inside sodalite or nosean “cages” of suitable sizes to contain halogens and radionuclides. The mercury vaporizes and is captured in the offgas system. The ^{99}Tc and ^{129}I are largely but not entirely retained in the mineral waste form initially, and any that escapes is captured in the offgas system and recycled into the DMR to improve retention. No liquid waste is discharged from the FBSR system, as the system is operated such that all of the water produced in the offgas system is recycled to the DMR and eventually vaporized, treated in the offgas system, and then discharged to the atmosphere.

In the FBSR facility, two process systems operate in parallel to receive waste from a single feed system to provide the throughput and ability to vary the flow rate needed to maintain the supplemental LAW feed vector throughput. Alternative FBSR 1A (Figure 3.3-3) produces a granular product that is then converted to a monolithic primary waste form for storage and permanent disposal in the IDF on the Hanford Site.

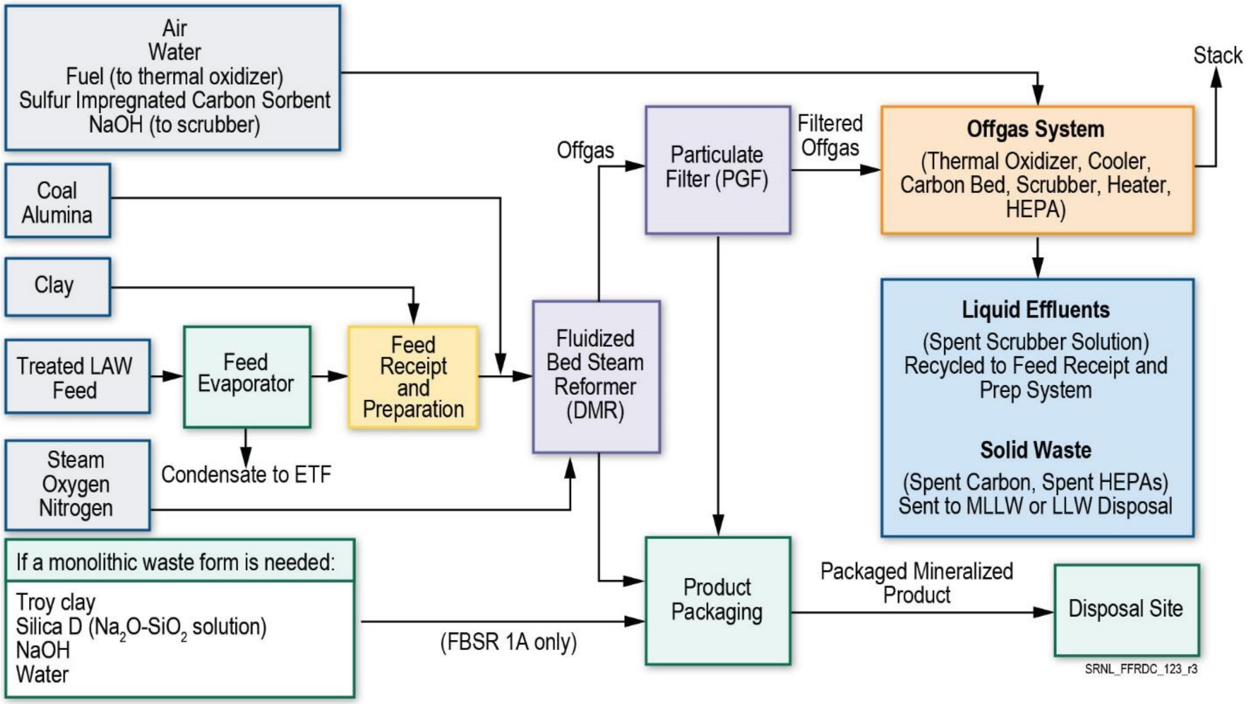

Figure 3.3-3. FBSR 1A, Fluidized Bed Steam Reforming with On-Site Disposal

A geopolymer process downstream of the FBSR converts the granular FBSR product to a monolith, which is needed to meet the 85 lb/in.^{2} (6 kg/cm^2) compressive strength limit required for IDF disposal. That step is part of the product packaging box in Figure 3.3-3, and consists of forming a grout-like waste form in containers, similar to that described below for grouting tank waste. The geopolymer process entails mixing granular FBSR product with clay, silica, caustic, and water, which is then poured into containers and cured, prior to disposal.

3.3.3 Alternative Grout 4B, Off-site Vendor for Grouting with Off-site Disposal

Extensive experience using grout waste forms has been gained in the U.S. from federal and commercial applications and as the standard immobilization technology for low-level waste (LLW) across the international community. This experience includes grouting of the supernatant portion of the tank waste at SRS[34] after treatment of the waste to remove soluble cesium, strontium, and actinides. At SRS, the grouted waste is disposed of in large on-site vaults adjacent to the Saltstone Facility. The required properties of the grout waste form in this alternative are dictated by the disposal location, the immobilization facility requirements, and chemistry of the waste. Grouting was also used to immobilize the separated LAW fraction of tank waste at the West Valley Demonstration Project, with the waste being subsequently disposed of at the Nevada Nuclear Security Site. Detailed descriptions are provided in Volume II, Appendix L.

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[34] While some differences exist between the SRS and Hanford wastes, the SRS waste is the closest analog in the U.S. to the waste at the Hanford Site.

This alternative uses an off-site vendor to immobilize the treated supernatant liquid. In alternative Grout 4B, the existing DST system is assumed to be used to blend and stage the feed. Waste would first be characterized to confirm its acceptability for the off-site disposal facility to ensure that the waste produced is compatible with grouting after pretreatment and LDR organic treatment (if needed), or if not compatible, the waste would be staged for vitrification. This alternative also provides the ability to begin supplemental LAW treatment and disposal as early as 2027.

After removal of ^{137}Cs and ^{90}Sr in TFPT and LDR organic treatment, if required, the treated supernatant liquid is shipped offsite in liquid form.[35] Multiple vendors are currently available that have the technical ability to grout the waste, and one or more could be used for this service. The vendor would mix the liquid waste with grout-forming additives, ordinary portland cement (OPC), blast furnace slag (BFS), and fly ash (FA). Other additives may be used or ratios may vary, depending on composition and disposal requirements.

The grout is poured into containers, assumed to be 10 yd^3 (8.4 m^3) steel boxes that can be disassembled, each with a heavy-duty polypropylene bag liner, although other sizes, configurations, and containers may ultimately be used. Unless the disposal site is also the vendor that performs grouting, the grouted waste, compliant with respective facility waste acceptance criteria, is then sent to an off-site facility for disposal. In either case, the waste is emplaced at the disposal site (Energy*Solutions* [Clive, Utah] and/or Waste Control Specialists [Andrews, Texas]). Figure 3.3-4 shows alternatives Grout 4B, including off-site disposal.

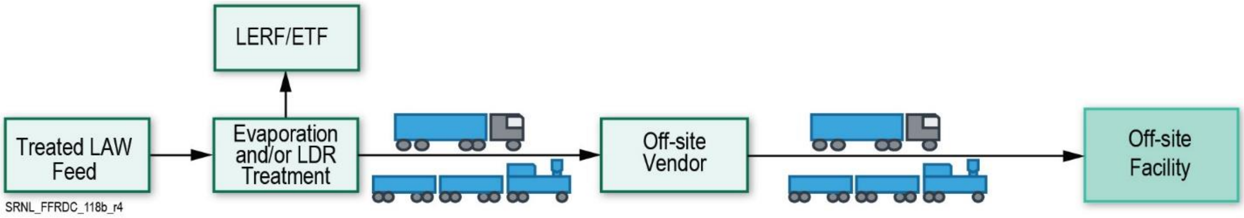

Figure 3.3-4. Flow Diagram for Alternative Grout 4B

Technical maturity for the immobilization process is high and could be performed with existing technology, assuming that the LDR organics can be removed by a separate process, if needed, for Clive disposal. This alternative could provide an early start and/or supplemental capacity for grout stabilization of the LAW.

Several factors minimize the potential for producing containers of the waste form that cannot be disposed offsite. A grouting process has a limited working inventory of liquid waste, although containers are assumed to not be shipped until some curing time has elapsed. If a problem occurs with disposal, shutting down grout production equipment is simple, limiting the material in interim status. With an extensive knowledge base of grouting comparable liquid waste, producing unacceptable grout is unlikely. Further, establishing agreements with two disposal sites in different locations minimizes the risk of producing waste with no defined disposal path.

Although not specified, the off-site vendor is assumed to have a process similar to that envisioned for the other grout alternatives evaluated in this document. That simplified typical containerized grout production flowsheet is provided in Figure 3.3-5, showing off-site disposal of the primary and secondary wastes. Secondary wastes from grouting are estimated to be small, and standard commercial practice is for the vendor to handle management and disposal.

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[35] The ability to ship pretreated liquid tank waste at a small scale (3-gallon proof of concept) was demonstrated during the Hanford TBI (DOE-EM, 2018).

Grouting alternatives are based on the assumption that the waste meets regulatory requirements for LDR organics. If the liquid waste requires treatment for LDR organics, they are removed by evaporation and possibly further using methods such as low temperature oxidation. All flowsheets for grout immobilization show an on-site evaporation and LDR treatment step for consistency, although it may not be needed for some wastes. If some portion of the waste is resistant to these treatments to remove or destroy the organics, the waste is assumed to be diverted to the LAW melter for processing.[36]

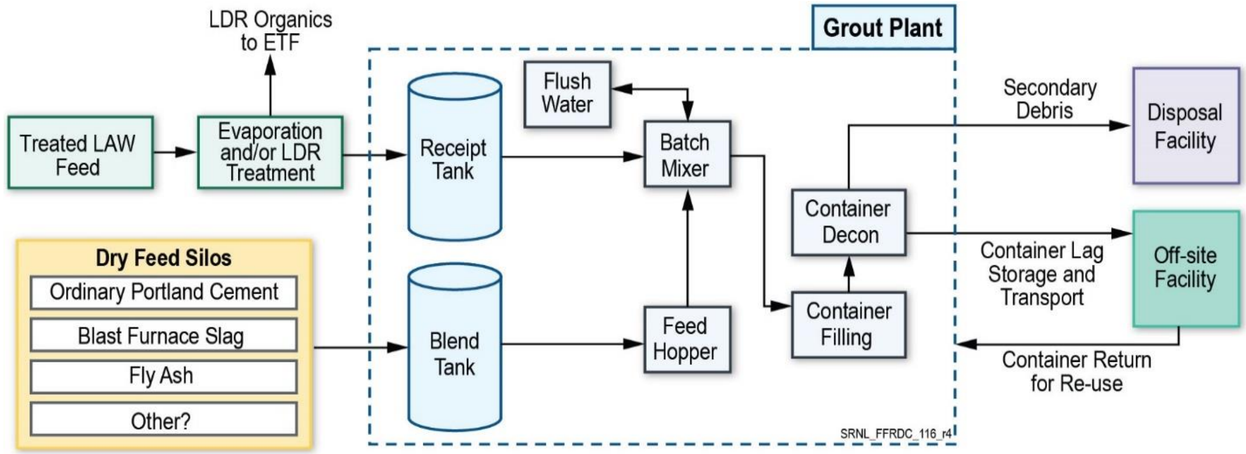

Figure 3.3-5. Typical Containerized Grout Processing Facility

Waste evaporation to both remove LDR organics and reduce waste volume are relatively mature technologies, although the effectiveness of LDR organic removal of all species is yet to be completely demonstrated. Additional treatment may be necessary to destroy some organics; any such technology has a low technical maturity level for application in Hanford tank wastes.[37] This alternative assumes that the liquid waste is sampled, analyzed, and tested as necessary prior to processing to ensure pretreatment will produce an acceptable waste form. Unlike the vitrification and FBSR alternatives, non-LDR constituents in the waste, including nitrate and nitrite ions, are not destroyed nor is NO_x vapor formed in the grouting process; these species are instead incorporated into the final waste form. Off-site disposal of a grouted waste form containing the nitrate and nitrite is anticipated to comply with the facility waste acceptance criteria and to have no impact on LDR constituents. Volume II, Appendix E, Section E.3.1.5 provides more information on nitrates/nitrites, and Volume II, Appendix A., Section A.3.6 and Appendix E, Section E.3.1.6 provides more information on LDR organics.

3.3.4 Alternative Grout 6, Phased Off-site and On-site Grouting in Containers

After evaluating the alternatives against the selection criteria, the lower construction and operating costs of all grout alternatives and the availability of off-site solidification/immobilization and disposal was found to offer the opportunity of phased implementation and early startup. This hybrid approach initially sends some pretreated low-activity liquid waste to an off-site facility for solidification/ immobilization by commercial treatment contractors and disposal at licensed off-site facilities. This approach also allows deferment of the design and construction phases of an on-site facility for the alternative. Of the alternatives with on-site immobilization, only the alternatives with on-site grout capital projects offered the financial opportunities to spend funds on these early off-site shipments. The Vitrification and FBSR alternatives required all of the assumed available benchmark funding to support the timely execution of capital projects, and any funds diverted from the projects for off-site shipments would delay the capital projects and/or increase the size of the project(s).

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[36] An acceptable method to transfer the diverted waste to the WTP LAW Vitrification Facility is assumed.

[37] Low temperature oxidation was planned for treatment of organics during the initial TBI, but was not needed because the organic concentrations were below action limits.

Any additional funding expended on off-site grouting without additional funds provided would delay the startup of supplemental LAW treatment operations and further delay completion of the WTP HLW Vitrification Facility mission. Therefore, only hybrid alternatives that involve grout as the final waste form were considered.

The FFRDC team considered several potential hybrid on-site/off-site grout alternatives. The alternative with the best combination of early progress and low risk was chosen for evaluation and designated alternative Grout 6. This hybrid alternative processing begins with one process in phases and transitions to a final process of on-site grout production and disposal. This hybrid alternative gives time to develop the waste form performance information and performance assessment modeling needed to complete remaining technology maturation (e.g., characterizing waste, determining grout formulations, and maturing additives/getters) to support the final phase of on-site disposal while simultaneously making progress and working within the assumed benchmark budget for the third phase to begin.

The eventual transition to on-site production and disposal in the final phase is expected to lower the overall mission cost and therefore the overall mission duration and risk. Of course, the on-site production and disposal alternative could instead be initiated immediately, avoiding off-site production and disposal. However, this approach is not the fastest at reducing risk of tank leaks, in part because it is reliant on the timing for approvals and the federal budget cycle, followed by grout plant construction time. If the off-site production and disposal is deemed infeasible due to unforeseen issues, the early construction and startup of the most favorable on-site alternative would be able to gain at least some advantage of the early removal of liquid waste from the tanks.

Another consideration is that there could be opportunities for co-locating a modular grout-production system, along with planned waste retrieval infrastructure in some tank farms; this approach was not fully evaluated as it is not envisioned to be the most cost-effective or fastest way to complete the entire LAW supplemental treatment mission, which is the objective of this evaluation. Using multiple modular systems was not fully evaluated for reasons described in Volume II, Section C.12, largely because of the need for constructing supporting infrastructure at multiple locations.

Alternative Grout 6 is a phased approach that combines aspects of alternatives Grout 4B (off-site vendor, off-site disposal) beginning in 2027 and aspects of Grout 2B (separate pretreatment plants with off-site grouting and disposal) in phased startup in 2034–2035, and transitions to on-site grouting in the 200 East Area with the on-site disposal approach beginning in 2040 (Volume II, Appendix C provides details on each alternative). Similar to alternative Grout 4B, waste would first be characterized to confirm its acceptability for the disposal facility to ensure that the waste produced has a defined disposal path. After removal of ^{137}Cs and ^{90}Sr in TFPT and LDR organic treatment, if required, the treated supernatant liquid is shipped offsite in liquid form. Since the off-site contractor is handling immobilization and disposal is offsite in this phase, the contractor would choose both the immobilization technique and the final packaging size and type. For this study, standard grout is assumed for costing purposes. Construction of the TFPT, LDR treatment, and a load-out station onsite would be needed, along with permitting for processing and disposal. The schematic for this phase is the same as that shown in Figure 3.3-4.

Multiple vendors are currently available that have the technical ability to grout the waste and one or more could be used for this service; additional permitted providers could also become available in the future. The schematic for the subsequent phase, comparable to pretreatment aspects of Grout 2B, is shown in Figure 3.3-6. A 200 East Area plant could instead perform grout production in this phase, along with off-site disposal in 2035–2039 (i.e., alternative Grout 2B), although this was not the assumed configuration in the cost profile.

The choice of on-site disposal scenario in Phase 3 (in containers in IDF similar to alternative Grout 1A or in a monolith/containers in a vault similar to alternatives Grout 5A or 5B) will be decided as a result of technology maturation and permitting activities before 2040. The alternative Grout 5B approach was assumed for costing in this phase, since this alternative is expected to be the most expensive of these three alternatives; however, the Grout 1A approach was used for the technical evaluation because the alternative is expected to have the lowest technical certainty, in part due to the need for getter development. Ultimately, if on-site grout disposal is found not viable, the backup option would be to dispose of all grouted waste offsite (i.e., continue as in alternative Grout 4B).

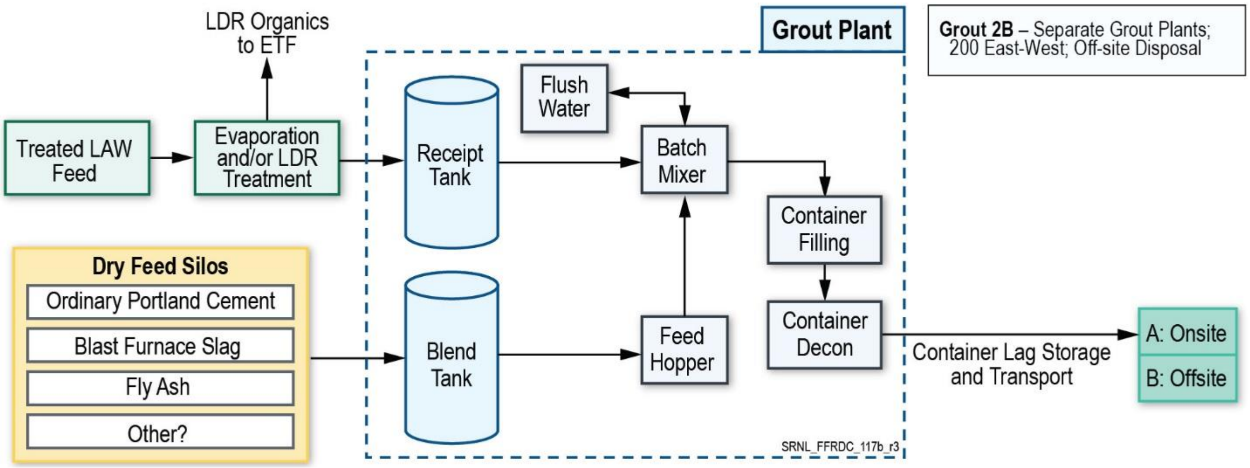

Figure 3.3-6. Schematic of Containerized Grout Production Onsite, with Off-site or On-site Disposal

The purpose of this alternative is to expedite retrieval and disposal of wastes. The hybrid concept of this alternative is to initially pretreat the waste in the 200 West Area, and a second phase consisting of the TFPT and LDR treatment process system would be constructed and operated in the 200 East Area. A second TFPT and LDR treatment process system would be constructed and operated in the 200 East Area, with the same off-site grouting and disposal steps, similar to alternative Grout 4B. Because much of the ^{99}Tc and ^{129}I is soluble and is at the highest concentration in the waste projected to be treated in the early phases, a disproportionate share (e.g., 10,000 Ci ^{99}Tc offsite versus 7000 Ci ^{99}Tc onsite) of the radionuclide inventory (as opposed to volume of waste) will be disposed of offsite. This “risk reduction” in alternatives Grout 4B and Grout 6 is discussed further in Section 3.4.

This alternative assumes off-site supplemental LAW treatment operations through the final years of DFLAW operations and in support of the WTP HLW Vitrification Facility startup. During the start-up and initial operations of the WTP HLW Vitrification Facility, the on-site grouting capacity will be developed and constructed in the 200 East Area. On-site grouting operations will commence in 2040 and run in parallel with off-site grouting until full capacity is realized. At this point, the WTP LAW Vitrification Facility and on-site grouting will suffice for balance of mission LAW feed immobilization. Although not included in this evaluation, if needed depending on the pace of the 200 West Area saltcake-rich SST retrievals, an additional grouting plant could be constructed near the SY Farm.

The evaluation of this alternative assumes that the iodine (^{129}I) getter is included in the grout formulation for the final phase, with on-site container disposal in IDF. However, the work in the interim period may identify that technetium and iodine removal or disposing the waste form as containers in vault (without getters) for on-site disposal is optimal (the vault approach was used for estimating). Unlike the vitrification and FBSR alternatives, non-LDR constituents in the waste, including nitrate and nitrite ions, are not destroyed nor is NO_x vapor formed in the grouting process; these species are instead incorporated into the final waste form.

Off-site disposal of a grouted waste form containing the nitrate and nitrite is anticipated to comply with the facility waste acceptance criteria and have no impact on LDR constituents. On-site disposal of the grouted waste form in Phase 3 is anticipated to be compliant with groundwater standards, but a performance assessment considering multiple variables, including the inventory to be disposed of onsite, would be required prior to disposal to assess groundwater impacts during the compliance and post-compliance periods.

Early start of LAW processing, particularly in the 200 East Area, alleviates DST space limitations and allows for the WTP HLW Vitrification Facility mission support as required for caustic dissolution of aluminum and sludge washing. These support operations will likewise generate LAW feed; the additional feed will be processed in conjunction with existing and SST retrieved supernatant liquids.

3.4 Risk Reduction and Mission Cost Profile as a Function of Low-Activity Waste Supplemental Treatment

Supplemental LAW treatment is needed to increase the work-off rate of the tank waste volume to support the overall retrieval/storage/preparation system capacity to allow HLW vitrification to effectively pace the RPP clean-up mission. This function is the reason supplemental LAW treatment was first proposed. The start-up and operations of supplemental treatment have a significant impact on the overall mission, as demonstrated by the previously discussed TOPSim results. The risk reduction (gallons and curies removed) and relationship to incurred cost versus time for the four selected alternatives is shown in Table 3.4-1.[38,39] There is a significant difference among alternatives regarding potential technetium disposition. This is due to the concentration of technetium in the initial LAW feed.

The initial LAW feed is currently the supernatant liquid in the DSTs and is significantly enriched in soluble technetium versus the precipitated salt in the SSTs.[40] In effect, while the volumetric reduction capabilities of LAW supplemental treatment are closely tied to the overall mission duration, the disposition of technetium is more closely connected to the initiation of LAW feed consumption.
For reference, the WTP LAW Vitrification Facility will process nominally 10,000 Ci of technetium in the first 27 years of operations (2023–2050) during the Vitrification 1 (modified) TOPSim model run scenario, but just under 2,000 Ci of technetium in the final 25 years (2050–2075). Analogously, if DFLAW operations are delayed past 2023, proportionately greater technetium/iodine would be processed via early off-site disposition options and removed permanently from the Hanford Site.

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[38] The TSCR unit constructed to support the DFLAW program started to generate feed in January 2022.

[39] Key mission activity dates reflect the last year prior to facility start. For reference, the current target date for HLW vitrification start is December 31, 2033. For vitrification, the assumed 2048 start of operations is consistent with the earliest projected start, allowing for 2 years additional operations and maximum technetium incorporation for that alternative (Vitrification 1).

[40] Technetium is distributed in the various quadrants based on the plutonium separations facility location and mission timing. Technetium in the northwest and northeast quadrants is derived from T and B Plant operations, respectively. These plants operated from the Manhattan project era and effectively split the incoming fuel (technetium source) through 1956. A small amount of technetium was processed through the REDOX plant located in the southwest quadrant. From 1956 on, the majority of fuel was processed at the PUREX plant, with fission products distributed throughout the southeast quadrant.

Table 3.4-1. Comparison of Cost and Projected Performance of Four Selected Low-Activity Waste Supplemental Treatment Alternatives

LAW Supplemental Treatment Alternative	Cumulative unescalated cost | Constant FY 2023 value ($M, rounded)				Cumulative supplemental LAW feed treated Mgal | Ci (Tc)			
	2033[a]	2039[b]	2047[c]	At Treatment Alternative Mission End[d]	2033[a]	2039[b]	2047[c]	At Treatment Alternative Mission End[d] (% Tc treated)
Vitrification 1	2,200 | 4,100	5,600 | 6,800	8,100 | 10,400	23,400 | 27,000 [2075[d]]	-	-	-	83[e] | 6,640 (27%)
FBSR 1A	1,600 | 2,100	3,500 | 4,600	4,800 | 5,900	8,400 | 9,900 [2070[d]]	-	-	25 | 5,700[e]	86[e] | 10,210 (41%)
Grout 4B	1,300 | 1,300	2,500 | 2,600	4,000 | 4,100	6,400 | 6,900 [2066[d]]	14 | 6,900	34 | 10,100	58 | 12,600	97 | 17,000 (68%)
Grout 6	1,400 | 1,600	3,200 | 3,600	4,100 | 4,800	5,800 | 6,900 [2066[d]]	14 | 6,900	34 | 10,100	58 | 12,600	97 | 17,000 (68%)

[a] Key mission activity: 2033 – Start of HLW vitrification (assumed end of year).

[b] Key mission activity: 2039 – Start of FBSR for supplemental LAW treatment (assumed end of year).

[c] Key mission activity: 2047 – Start of vitrification for supplemental LAW treatment (assumed end of year).

[d] The mission end date varies by treatment technology.

[e] For alternative Grout 4B, the technetium curies dispositioned are taken directly from the TOPSim model run. Alternative Grout 6 (with same 2026 start date) is assumed to have the same feed vector – understanding that technetium treated from 2040 on (6,000 Ci) would be dispositioned onsite in IDF versus offsite. For alternative Vitrification 1, the technetium curies treated are adjusted from the Vitrification 1 (modified) TOPSim model run by adding 3× the nominal technetium curies treated by LAW vitrification over that same period. Technetium treated by dates for alternatives FBSR 1A and Grout 1A were similarly projected based on nominal LAW vitrification technetium performance – assuming the alternatives would see the same feed vector as LAW vitrification. Projected volumes for process alternatives were calculated in a similar manner using the annual feed volumes projected for the process alternatives in this study and bounded by the TOPSim modeling results.

[f] Grout 1A is included in this chart to reflect the performance with respect to gallons of supplemental LAW treated and curies treated. Grout 1A is consistent with all Grout 1, 2, 3, and 5 process feed vectors.

Ci = curie.
FBSR = fluidized bed steam reforming.
FY = fiscal year.
HLW = high-level waste.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
MCi = million curies.
Mgal = million gallons.
Tc = technetium.

This concept is important as it demonstrates a diminishing return on technetium disposition versus volume processed. As the mission progresses from feed currently stored as supernatant liquid to feed derived from SST retrievals, there is noticeable reduction in technetium concentration. The supplemental LAW treatment technologies will all process between 80 and 100 Mgal (300 to 380 million L) of LAW feed. Alternatives with deferred starting dates will ultimately disposition fewer technetium curies via supplemental treatment, and force longer, higher cost missions. From that basis, alternative Vitrification 1, with the highest cost by a nominal factor of three and a disposition of one-third of the technetium curies, provides the lowest return on investment.

4.0 COMPARATIVE ANALYSIS

Section 3125 of NDAA21 lists specific factors to be considered in the FFRDC analysis, including some carried forward from Section 3134 of NDAA17. To the extent possible, GAO Best Practices and DOE G 413.3-22, *Analysis of Alternatives Guide*, were used during criteria development and performance of the comparison of alternatives. Existing frameworks were sought for decision-making that would be useful in the development of a taxonomy of criteria with maximum relevance to decision-makers when selecting an alternative to pursue. DOE and EPA frameworks (e.g., DOE G 413.3-22, EPA RCRA and CERCLA remedy selection methodologies) were used to provide a well-established basis in the development of criteria. These criteria were tailored to best apply in the context of supplemental treatment of LAW.

4.1 Decision Forming Criteria

The high-level criteria used in the comparative analysis were:

1. Long-term effectiveness (environmental and safety risk after disposal)
2. Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)
3. Likelihood of successful mission completion (including technical, engineering, and resource-related risks)
4. Lifecycle costs (discounted present value)

Long-term effectiveness (environmental and safety risk after disposal) assesses the long-term performance of the proposed waste form in its final disposal site. Assessment of this criterion for a given alternative addresses the estimated ability of the alternative to destroy or neutralize toxins, to immobilize toxins and radionuclides away from all potable water and natural environments, and any long-term greenhouse gas emissions from the final waste form(s) after disposal. This assessment also considers the degree of confidence in the performance estimates, based on past and ongoing research into waste form performance. All alternatives considered are expected to meet current applicable disposal requirements under RCRA, AEA, state, and NRC permitting requirements.

Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) assesses the risks to human safety and the environment during design, construction, commissioning, and operations of each treatment alternative. While the FFRDC team considered all physical, chemical, and radiological risks (and greenhouse gas emissions), those risks associated with the ongoing degradation of aging waste storage tanks at Hanford, the overall duration of activities to empty the waste tanks, and processing flexibility during operations had the strongest influence on the overall assessments.

Likelihood of successful mission completion (including technical, engineering, and resource-related risks) recognizes that the benefits of any alternative are only realized if the alternative can be executed to accomplish removal and disposition of all primary and secondary wastes. This criterion aligns closely with the "Implementability" criterion used in the RCRA and CERCLA guidance for development and screening of remedial actions. In addition to assessing technical and engineering risks to project and mission completion, the FFRDC team also assessed risks due to required resources, including peak annual funds and average annual construction costs. A benchmark budget of $450 million/year (fiscal year [FY] 2023 dollars, solely for supplemental LAW treatment activities) was used to estimate schedules and the impact of peak funding requirements on the likelihood of successful completion. Sensitivity to the level of the benchmark budget was assessed, confirming that the differences in qualitative scores for Criteria 2 and 3 among the alternatives are robust over a wide range of possible average annual budgets. Details of these sensitivity analyses are provided in Volume II, Appendix F.

Lifecycle costs (discounted present value) estimate the total commitment of public funds needed to implement each alternative. The construction estimates developed for this study were constrained to fit within a benchmark average annual funding level, and therefore are not directly comparable to past unconstrained estimates unless noted.[41] The budget constraint results in considerable construction schedule expansion for some of the alternatives, relative to their unconstrained project estimates. That schedule expansion in turn leads to additional costs, in addition to adding to duration-sensitive risks. The cost estimates developed for this analysis underestimate the cost impact of schedule delays, in that they do not account for inefficiencies in project execution resulting from reduced pace of implementation. Operations schedules, which are driven by the outputs of the WTP HLW Vitrification Facility processing, were not constrained in annual funding, nor were they allowed to stretch. Instead, any differences between the benchmark budget and the funds required to process LAW in particular years were calculated and accumulated. Discounted total excesses/shortfalls under the flat budget are reported for each alternative. Discounting, escalation assumptions, and sensitivity analyses (with unconstrained funding) are explained in Volume II, Appendix F.

For these four top-tier primary decision-informing criteria, a hierarchical taxonomy of relevant lower-tier criteria was developed to support systematic and structured analysis. Findings of prior research (including quantitative metrics where available) were incorporated into this taxonomy. The detailed lower-tier criteria were matched against the NDAA21 criteria to ensure that all were addressed in the analysis. The details of this comparative analysis are presented in Volume II, Appendix D. Assessment of the full taxonomy of criteria also provided the team with a detailed understanding of each alternative, including differences and similarities. Following the analysis of each alternative against lower-tier criteria using applicable measures of effectiveness, higher-tier criteria were iteratively evaluated based on the lower-tier findings and the team's expert judgment of the relative contributions of the criteria to risk and effectiveness. Once all tiers of the taxonomy had been evaluated for each alternative, the alternatives were analyzed comparatively based on the resulting assessments of the four top-tier criteria. A complete traceback of how the top-tier assessments derive from the lower tiers is provided in Volume II, Appendix D. A crosswalk showing how this taxonomy of criteria incorporates all of the factors and sources of evidence specified in the text of Section 3125 of NDAA21 is provided in Volume I, Appendix E.

Two other decision criteria relevant to decision-makers were identified by the FFRDC team, but were deliberately excluded from the direct comparison and ranking of alternatives, as discussed in Section 4.3.

5. Securing and maintaining necessary permits/authorities (regulatory approval)
6. Community/public acceptance (state/local)

During the assessment process, the FFRDC team adjusted the taxonomy as additional relevant factors and criteria were identified. In the end, only four to five distinct qualitative levels were assigned for each of Criteria 1 to 3, across the 15 specific alternatives considered. The team crafted text descriptions for interpretation of those levels and ranked them in order of desirability within each criterion.

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[41] Unconstrained estimates for the four selected alternatives are provided in Volume II, Appendix F.

4.2 Assessment Results

The results of the assessment process, and the specific alternatives scored at each level, are shown below.

- **Criterion 1**: Long-term effectiveness (environmental and safety risk after disposal) – also referred to in Figure 4.3-1, Figure 4.3-6, Figure 4.3-7, and Figure 4.3-8 as “performance” for brevity
  - Highly effective, low uncertainty (Grout 1B, 2B, 4B, FBSR 1B)
  - Effective, low uncertainty (Grout 1D)
  - Highly effective, moderate uncertainty (Grout 6)
  - Effective, moderate uncertainty (Grout 1C, 2C, 5A, 5B, FBSR 1A)
  - Moderately effective, moderate uncertainty (Grout 1A, 2A, 4A, Vitrification 1)
  - For Vitrification 1, further clarification was made that the vitrified waste form was assessed as highly effective, but the disposition of secondary wastes was only moderately effective.
- **Criterion 2**: Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration) – also referred to in Figure 4.3-1, Figure 4.3-6, Figure 4.3-7, and Figure 4.3-8 as “promptness”
  - 2027 operations, 2065 completion, low risk with flexibility (Grout 6)
  - 2027 operations, 2065 completion, moderate risk (Grout 4A, 4B)
  - 2036 operations, 2068 completion, low risk (Grout 1A, 1B, 1C, 1D, 2A, 2B, 2C, 5A, 5B)
  - 2040 operations, 2070 completion, high risk (technical) (FBSR 1A, FBSR 1B)
  - 2050 operations, 2075 completion, high risk (schedule) (Vitrification 1).
- **Criterion 3**: Likelihood of successful mission completion (including technical, engineering, and resource-related risks) – also referred to in Figure 4.3-1, Figure 4.3-6, Figure 4.3-7, and Figure 4.3-8 as “feasibility”
  - Considerable funding margin, very high probability of completion, low uncertainty (Grout 1A, 1B, 1D, 4A, 4B)
  - Moderate funding margin, high probability of completion, low uncertainty (Grout 1C, 2A, 2B, 2C, 5A, 5B, 6)
  - Low funding margin, low probability of completion, low uncertainty (FBSR 1A, FBSR 1B)
  - Significant funding shortfall, extremely low probability of completion, low uncertainty (Vitrification 1).
- **Criterion 4**: Lifecycle costs (discounted present value) – Discounted lifecycle costs comprise the costs required prior to the beginning of operations and the costs required for operations. This information is shown in Table 4.2-1 with ranking of alternatives from best (lowest cost) to worst (highest cost) based on the total discounted present value lifecycle costs.

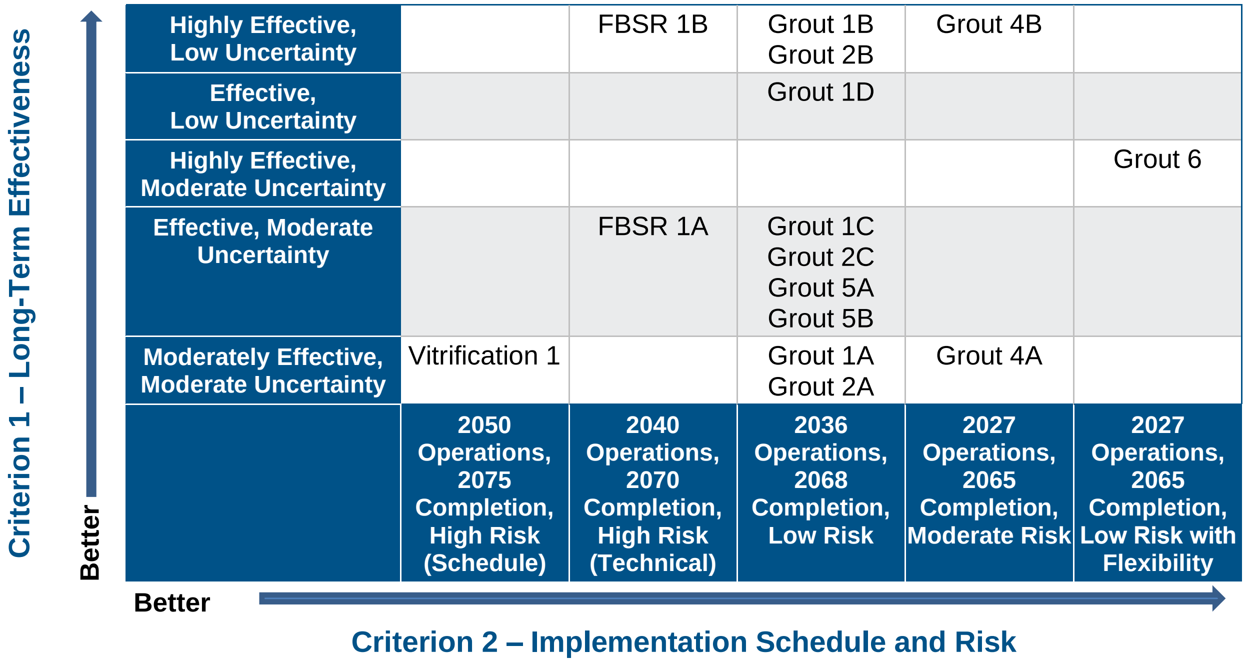
Table 4.2-1. Lifecycle Costs, Lowest to Highest (discounted present values, $M)

Alternative	Pre-Operations	Operations	Total
Grout 1A	1,108	1,622	2,730
Grout 1C, 1D	1,200	1,915	3,115
Grout 4A	411	2,927	3,338
Grout 5A, 5B	1,735	1,614	3,349
Grout 2A	1,544	1,851	3,395
Grout 1B	1,108	2,306	3,414
Grout 2C	1,636	2,211	3,847
Grout 4B	410	3,444	3,854
Grout 6	1,393	2,734	4,127
Grout 2B	1,544	2,774	4,318
FBSR 1A	3,375	2,152	5,527
FBSR 2A	3,374	2,905	6,279
Vitrification 1	7,608	5,092	12,700

FBSR = fluidized bed steam reforming.

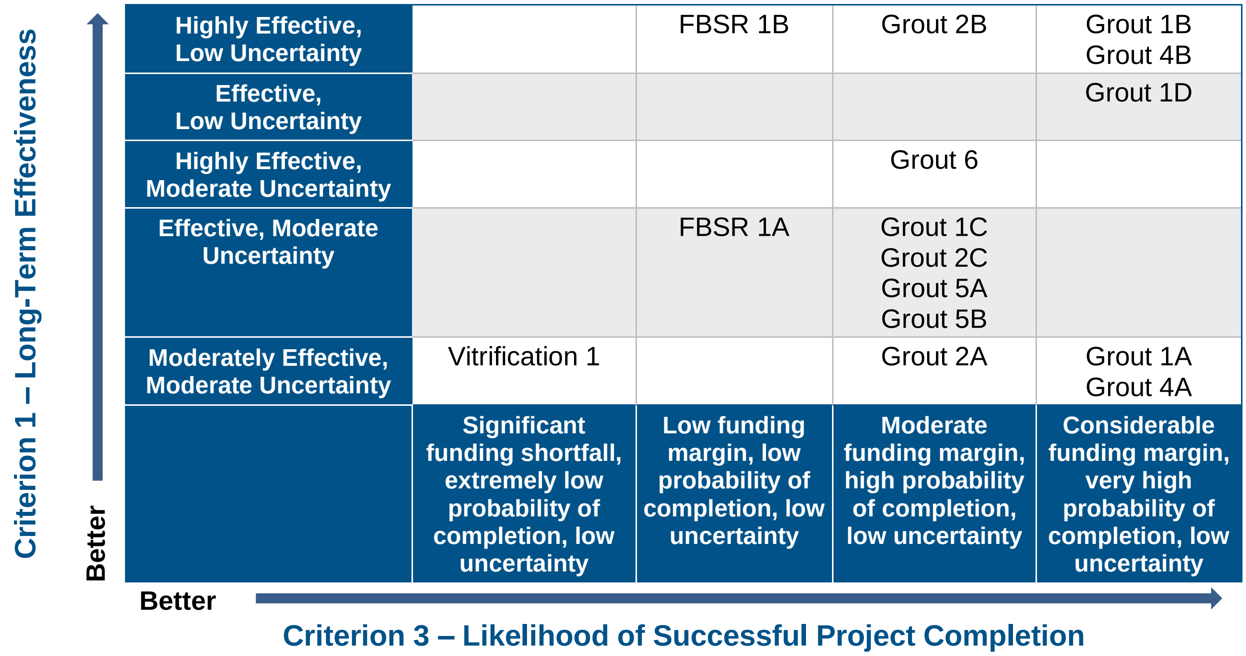
4.3 Comparative Analysis

Figure 4.3-1 through Figure 4.3-3 show the FFRDC team's assessments of the qualitative decision criteria (Criteria 1–3) in pairwise comparisons highlighting the tradeoffs in performance against the criteria for the alternatives.



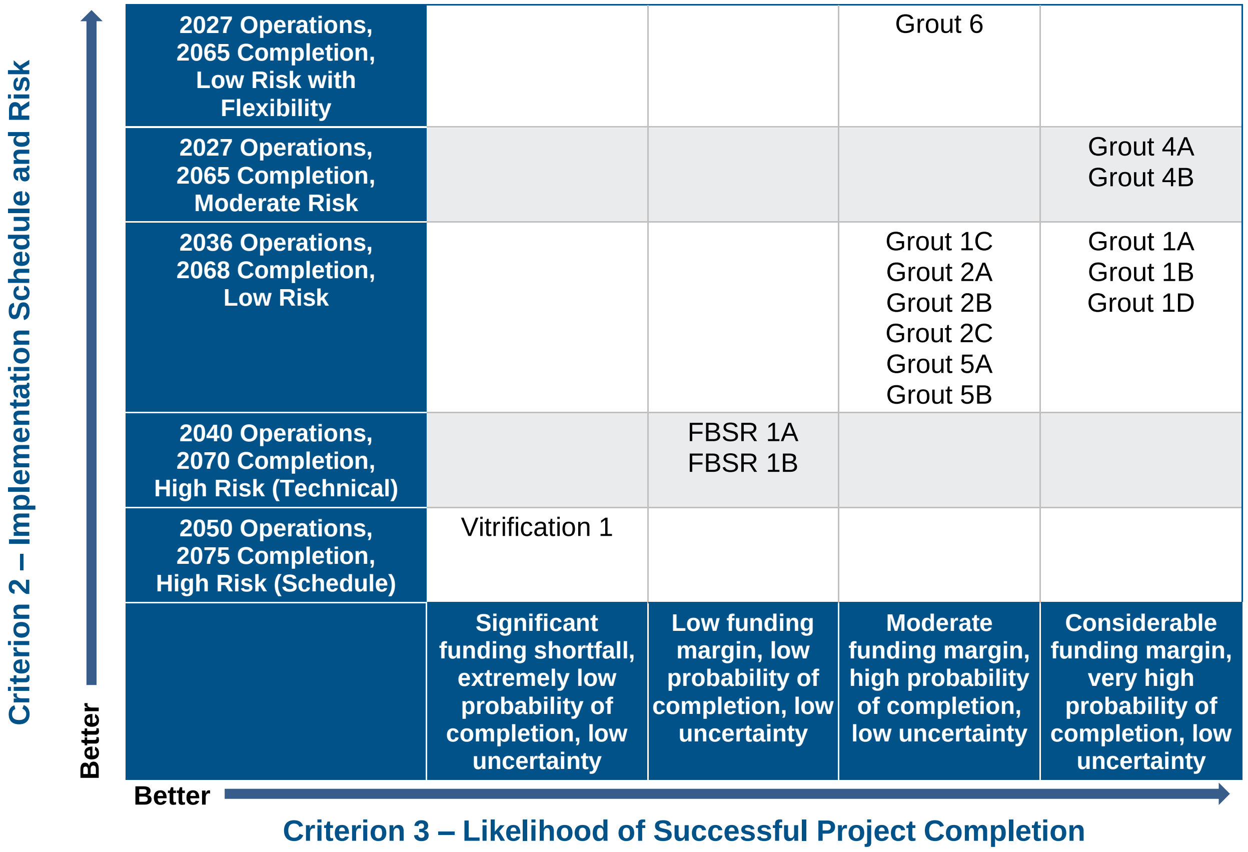
	2050 Operations, 2075 Completion, High Risk (Schedule)	2040 Operations, 2070 Completion, High Risk (Technical)	2036 Operations, 2068 Completion, Low Risk	2027 Operations, 2065 Completion, Moderate Risk	2027 Operations, 2065 Completion, Low Risk with Flexibility
Highly Effective, Low Uncertainty		FBSR 1B	Grout 1B Grout 2B	Grout 4B	
Effective, Low Uncertainty			Grout 1D		
Highly Effective, Moderate Uncertainty					Grout 6
Effective, Moderate Uncertainty		FBSR 1A	Grout 1C Grout 2C Grout 5A Grout 5B		
Moderately Effective, Moderate Uncertainty	Vitrification 1		Grout 1A Grout 2A	Grout 4A	

Figure 4.3-1. Pairwise Comparison, Performance and Promptness



	Significant funding shortfall, extremely low probability of completion, low uncertainty	Low funding margin, low probability of completion, low uncertainty	Moderate funding margin, high probability of completion, low uncertainty	Considerable funding margin, very high probability of completion, low uncertainty
Highly Effective, Low Uncertainty		FBSR 1B	Grout 2B	Grout 1B Grout 4B
Effective, Low Uncertainty				Grout 1D
Highly Effective, Moderate Uncertainty			Grout 6	
Effective, Moderate Uncertainty		FBSR 1A	Grout 1C Grout 2C Grout 5A Grout 5B	
Moderately Effective, Moderate Uncertainty	Vitrification 1		Grout 2A	Grout 1A Grout 4A

Figure 4.3-2. Pairwise Comparison, Performance and Feasibility

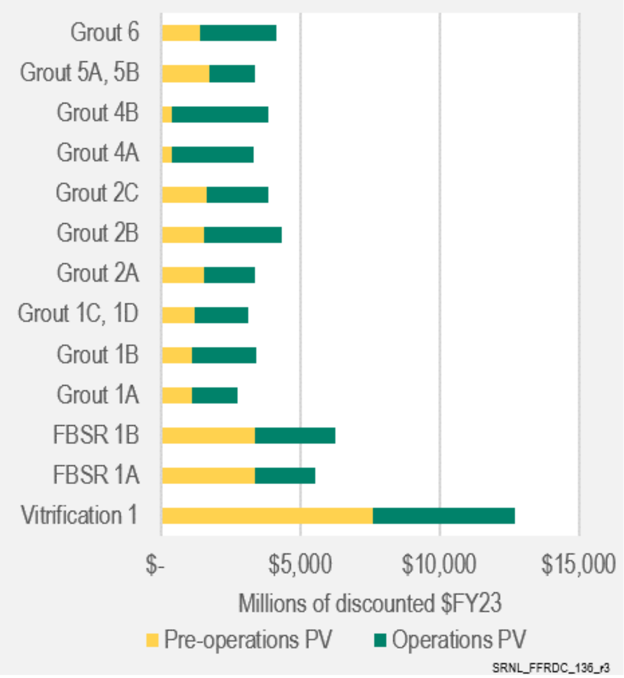


	Significant funding shortfall, extremely low probability of completion, low uncertainty	Low funding margin, low probability of completion, low uncertainty	Moderate funding margin, high probability of completion, low uncertainty	Considerable funding margin, very high probability of completion, low uncertainty
2027 Operations, 2065 Completion, Low Risk with Flexibility			Grout 6	
2027 Operations, 2065 Completion, Moderate Risk				Grout 4A Grout 4B
2036 Operations, 2068 Completion, Low Risk			Grout 1C Grout 2A Grout 2B Grout 2C Grout 5A Grout 5B	Grout 1A Grout 1B Grout 1D
2040 Operations, 2070 Completion, High Risk (Technical)		FBSR 1A FBSR 1B		
2050 Operations, 2075 Completion, High Risk (Schedule)	Vitrification 1			

Figure 4.3-3. Pairwise Comparison, Promptness and Feasibility

Figure 4.3-4 shows the total discounted cost (present value) for each of the 15 alternatives. (Volume II, Appendix F, Section F.2.2 provides definitions of present value and discounting terminology.)

To permit visual comparison of the alternatives, the FFRDC team calculated rank values for each alternative against each criterion. These scores denote the number of alternatives that scored worse on that criterion, among the 15. Higher values thus indicate better performance. The figures do not indicate relative scores of the criteria. The bars in the figures reflect the number of alternatives that scored worse than a particular alternative for that criterion. This convention means that some alternatives are not shown in a figure because they did not score better than any alternative for that particular criterion.



FY = fiscal year, PV = present value.

Figure 4.3-4. Lifecycle Costs of Alternatives

Figure 4.3-5 shows these rank values graphically. This method of comparison generally understates the magnitude of the qualitative differences in the assessments for Criteria 1–3. The details of the underlying assessments for the qualitative criteria (Criteria 1–3) are provided in Volume II, Appendix D.

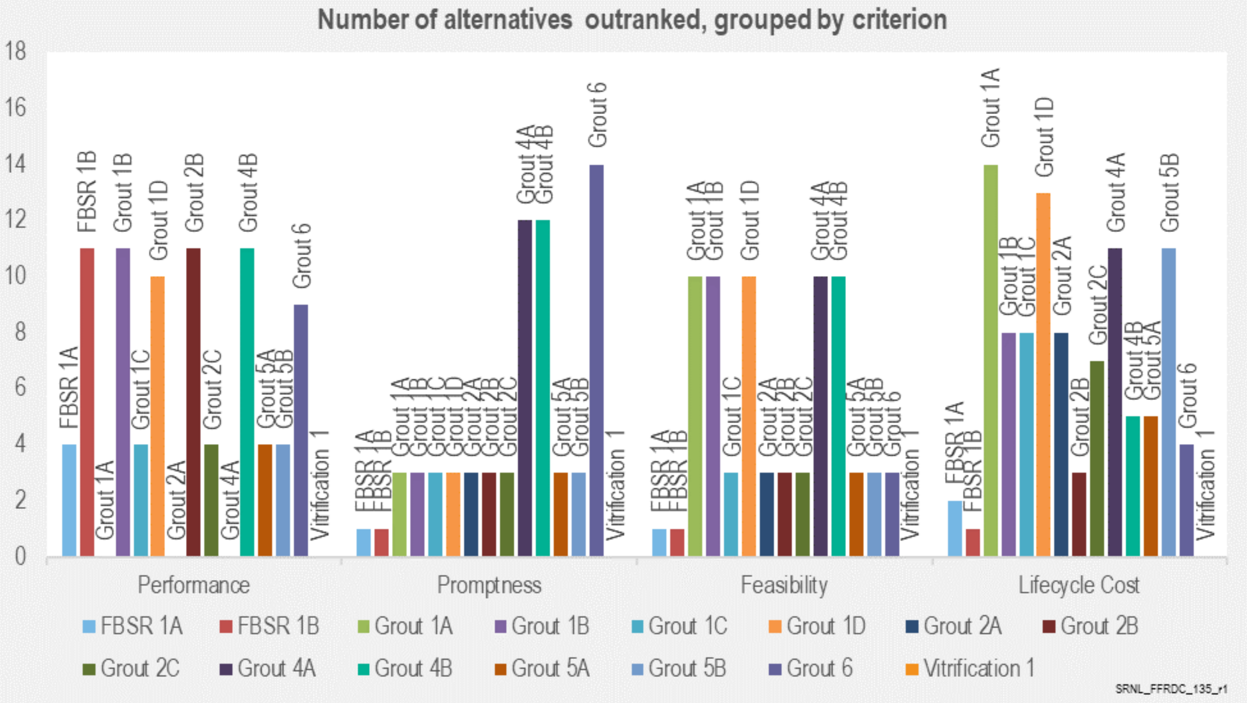


Figure 4.3-5. Number of Alternatives Outranked, by Criterion

As described in Section 3.3, the FFRDC team selected four alternatives that were considered the best representatives of the treatment technologies: FBSR 1A, Grout 4B, Grout 6, and Vitrification 1. Figure 4.3-6 shows the rank value comparison for only these four alternatives, grouped by criterion. Figure 4.3-7 shows the same comparison, grouped by alternative. Because Vitrification 1 does not outrank any other alternatives, its representative bars do not appear in these figures.

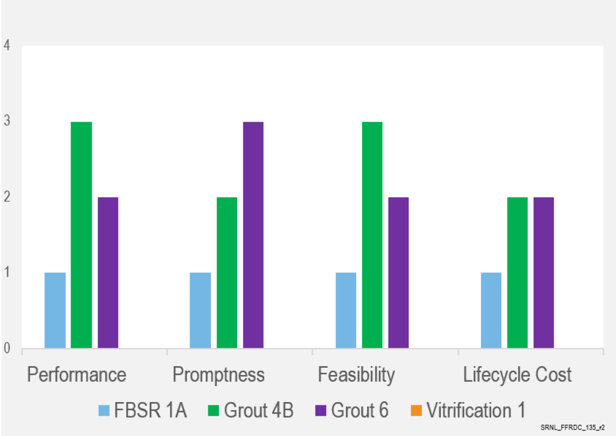


Figure 4.3-6. Number of Alternatives Outranked, Four Selected Alternatives, Grouped by Criterion

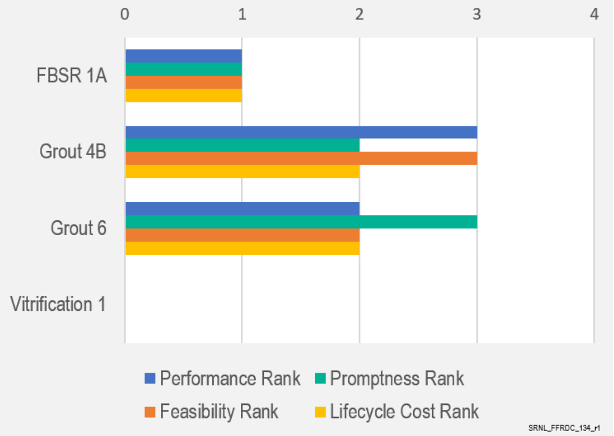
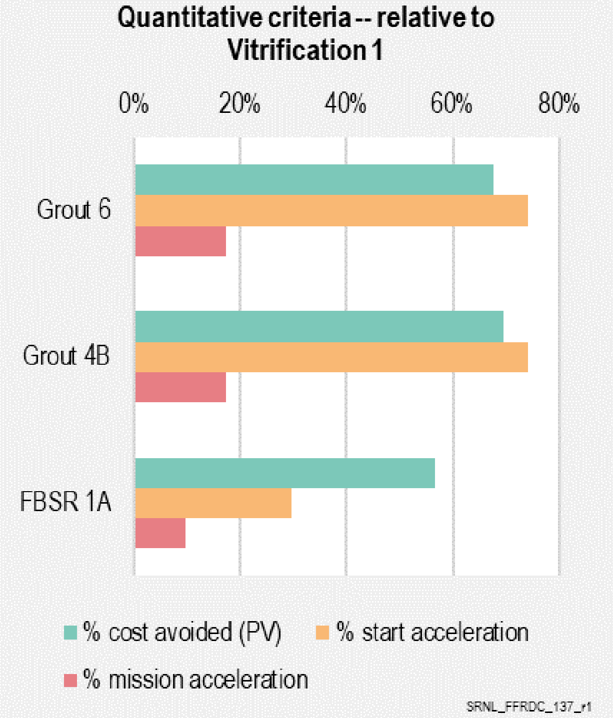


Figure 4.3-7. Number of Alternatives Outranked, Four Selected Alternatives, Grouped by Alternative

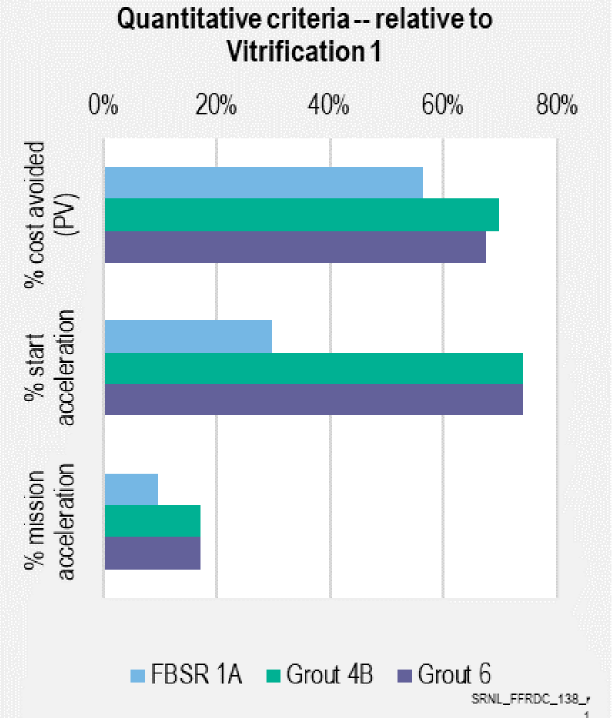
Figure 4.3-8 compares the cost and schedule reduction relative to alternative Vitrification 1 for the four selected alternatives. Figure 4.3-9 shows the same comparison, grouped by criterion.



Start acceleration = the number of years before treatment of supplemental treatment of LAW can begin.

Mission acceleration = the number of years before the last supplemental waste is treated.

Figure 4.3-8. Cost and Schedule Reduction Relative to Alternative Vitrification 1



Start acceleration = the number of years before treatment of supplemental treatment of LAW can begin.

Mission acceleration = the number of years before the last supplemental waste is treated.

Figure 4.3-9. Cost and Schedule Reduction Relative to Vitrification, Grouped by Criterion

To depict relative cost and schedule desirability of alternatives, the FFRDC team noted that the Vitrification 1 alternative had the greatest cost, the longest delay to beginning supplemental treatment of LAW, and the latest completion of the treatment mission. Cost and schedule assessments were therefore measured as the costs or duration avoided relative to the Vitrification 1 alternative.

Figure 4.3-10 shows the tradeoffs between cost avoidance and time to begin supplemental treatment of LAW among the 15 alternatives.

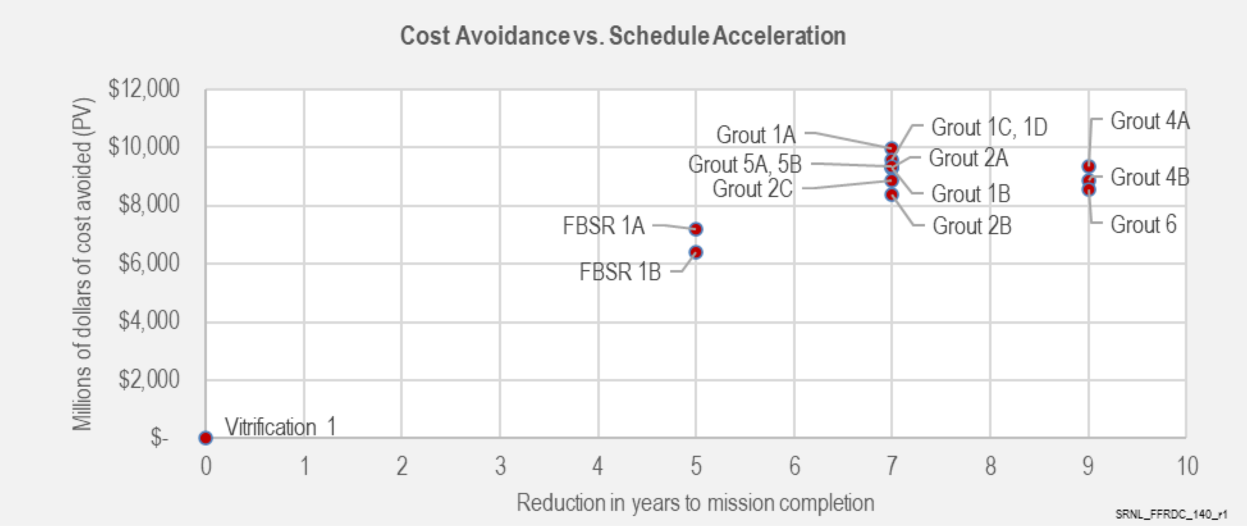


Figure 4.3-10. Cost Avoidance vs. Schedule Acceleration, Overall Mission

Figure 4.3-11 shows the analogous tradeoffs between cost avoidance and time to complete the RPP mission.

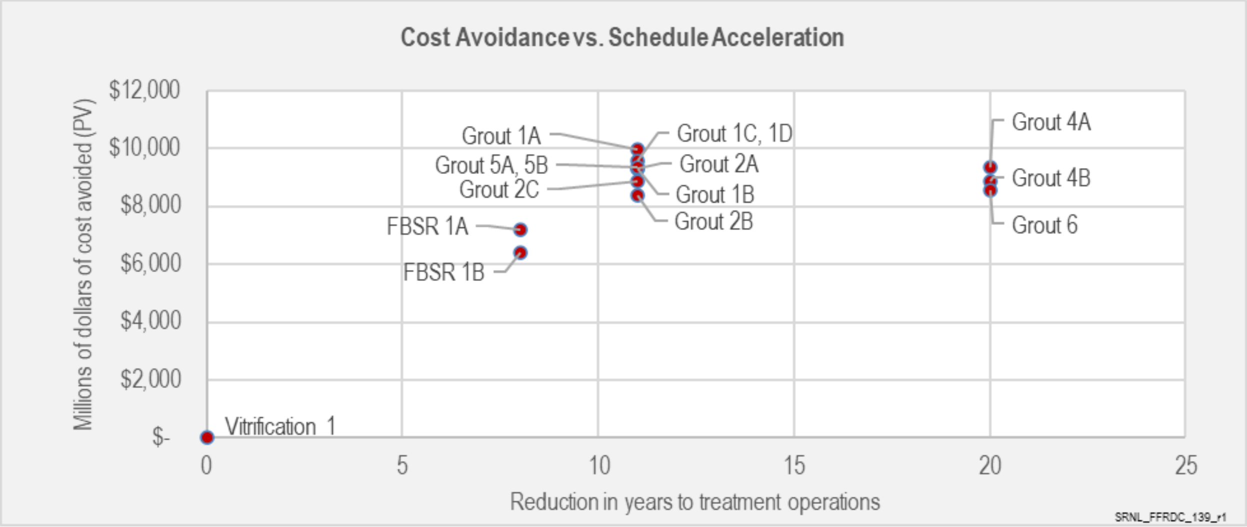


Figure 4.3-11. Tradeoff of Cost Avoidance vs. Schedule Acceleration, Start of Supplemental Treatment

For Criteria 5 and 6, the FFRDC team concluded that decision-makers should have the benefit of this and other analyses (e.g., by NASEM, GAO) prior to formulating input as part of the decision-making process. Likewise, securing regulatory approval is part of the negotiation process between government agencies, and it would be inappropriate for the FFRDC team to assign likelihood of specific outcomes. These criteria are included in the taxonomy but not included in the roll-up with the other criteria.

5.0 RESULTS USING THE DECISION FRAMEWORK

The FFRDC team used the top-tier criteria assessments to directly compare alternatives. Table 5-1 includes a high-level summary of results that can serve as a decision framework for decision-makers to inform their decisions regarding supplemental LAW treatment technologies and disposal locations. The table includes representative alternatives for each technology.

Table 5-1. High-Level Comparison of the Four Selected Alternatives for Supplemental Treatment of Low-Activity Waste

Alternative			
Vitrification 1: Disposal onsite at Hanford	**FBSR 1A: Solid monolith product disposal onsite at Hanford**	**Grout 4B: Off-site grouting/disposal**	**Grout 6: Phased Approach Off-site grouting/ disposal, then on-site grouting/disposal**
Criterion 1: Long-term effectiveness (environmental and safety risk after disposal)			
Highly effective for primary waste; moderately effective for secondary waste. Medium confidence in the assessment.	Effective. Medium confidence in the assessment, due to technology immaturity.	Highly effective. High confidence in the assessment.	Highly effective. Good to high confidence in the assessment.
Criterion 2: Implementation schedule and risk (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)			
High risk due to significant cost-based startup delays and operations limits. Moderate technical implementation risk. Construction finishes and treatment starts in 2047, mission does not complete without significant additional annual budget.	High risk due to construction time required and technical execution risk. Construction finishes and treatment starts in 2039; mission completes 2070.	Low risk due to earliest potential start of treatment in 2027, minimal construction, low-temperature process, likely capacity, and modest transportation and operations costs. Limited facilities (e.g., evaporator and load-out station) needed; mission completes 2066.	Very low risk due to earliest start of treatment in 2027, flexible timing of conversion to on-site low-temperature process, and inexpensive operations. Grout plant construction finishes 2039; mission completes 2066.
Criterion 3: **Likelihood of successful mission completion** (including technical, engineering, and resource-related risks)			
Very low probability of successful completion due to resource intensity.	Low probability of successful completion, due to technical risk.	Very high likelihood of successful completion.	High likelihood of successful completion.
Criterion 4: Lifecycle cost (discounted present value)			
$7.6B construction; $5.1B operations (total operations costs exceed benchmark budget by $1.2 B)	$3.4B construction; $2.2B operations	$0.4B construction; $3.4B operations	$1.4B construction; $2.7B operations

FBSR = fluidized bed steam reforming.

Alternative Vitrification 1 has a very low likelihood of mission completion because both peak estimated construction costs and estimated annual operating costs significantly exceed the benchmark budget, and this finding is not sensitive to the exact budget assumed. The cumulative shortfall for operations, relative to the benchmark budget, has a present value of $1.2 billion. Vitrification 1 is the only alternative that was found to consistently exceed the benchmark in all sensitivity cases, and is assessed as least likely to complete as designed. Vitrification 1 also has a longer delay until the start of operations compared to other alternatives, with supplemental treatment of LAW beginning in 2050. The delayed completion of construction and the length of operations increase environmental risk associated with the degradation of the waste storage tanks. The vitrified waste is expected to be highly effective in the long-term; however, the secondary waste produced by vitrification, which will be disposed of onsite, is expected to be only moderately effective.

The present value of lifecycle costs is $12.7 billion for Vitrification 1, which is more than twice the present value of lifecycle costs of FBSR 1A and more than three times greater than the present value of lifecycle costs of Grout 4B or 6.

Alternative FBSR 1A also has a low likelihood of mission completion, but due to technical risk, as FBSR is considered a first-of-a-kind technology for Hanford LAW and carries a great deal of uncertainty in the treatment process. The low technical maturity necesitates testing and development not required for the vitrification and grout alternatives, which contributes to delaying construction completion until 2039 and increases environmental risks related to storage tank degradation. While the FBSR waste form is expected to have acceptable long-term effectiveness, there is less confidence relative to the Vitrification 1 and Grout 4B and 6 waste forms.

Alternatives Grout 4B and Grout 6 have very high and high likelihoods of successful completion, respectively. While both have less construction and lower annual costs when compared to the vitrification and FBSR alternatives, Grout 4B construction is limited to an evaporator and loading facilities, while Grout 6 eventually constructs a grout plant. Both Grout 4B and 6 start treatment by an off-site vendor in 2027 and complete operations in 2065, thus reducing environmental risks related to storage tank degradation and have low and very low risks, respectively, with Grout 6 risk being lower due to the availability of two treatment options and the flexibility to delay grout plant construction. Both are highly effective with regard to long-term performance of the waste form, with a slight advantage to Grout 4B for all waste disposed of at an off-site location. The first phase of Grout 6 results in a large inventory of technetium and iodine being disposed of offsite. By the time this hybrid alternative shifts to on-site disposal, the technetium and iodine concentrations are expected to be much lower than those in the grouted secondary waste of Vitrification 1, which concentrates radionuclides in a smaller volume than the grout alternatives. Grout 6 is therefore expected to be more effective for long-term performance than Vitrification 1.

A risk with respect to out-of-state treatment/disposal options is the possibility that the resulting LAW might not be acceptable to the receiving facility – or to the regulatory authorities of transit or receiving states – and accordingly cannot be shipped from Hanford or returned to Hanford with no disposal path. As discussed in Volume I, Appendix D, and Volume II, Appendix H, all shipments to these two sites will need to meet all NRC and U.S. Department of Transportation requirements with which DOE and its contractors have extensive experience. At present, both the Waste Control Specialists (Andrews, Texas) and Energy*Solutions* (Clive, Utah) treatment/disposal sites are licensed to receive Class A waste, and 83 to 93% of grouted Hanford tank supplemental LAW is projected to fall within Class A (Volume II, Appendix H, Table H.3). Accordingly, the majority of the tank LAW likely meets the current waste acceptance criteria at both facilities and any state-imposed permit conditions.

The decision-informing criteria and the detailed criteria taxonomy appear in Volume I, Appendix A, and the details of the assessment of these four alternatives are provided in Volume I, Appendix B and Appendix C.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Several overarching observations and conclusions result from analysis of the alternatives:

1. Only grout-based alternatives allow the near-term disposition of LAW that achieves the fastest reduction of risk of future tank leaks. FBSR and vitrification do not allow the near-term supplemental treatment of LAW. There is a range of more than two decades in start-up schedules for the three technologies.
2. Processing flexibility for LAW is an important consideration. Flexibility is manifested through (1) the range in processing rates that the selected technology can readily achieve to accommodate disruptions, increases, and decreases in LAW processing; (2) the availability of different treatment technologies to adapt to variabilities and uncertainties in LAW characteristics; and (3) avoidance of single-point failure mechanisms (e.g., only having a single treatment facility or disposal facility vailable). If a technology other than vitrification is selected, vitrification will still be available through the WTP LAW Vitrification Facility for any wastes that are not amenable to that supplemental treatment process.
3. Grout alternatives are clearly executable at benchmark funding levels and have the highest probability of successful completion. FBSR alternatives might be executable within the benchmark budget but carry first-of-a-kind technical risks for Hanford LAW disposition. FBSR has higher annual cost and higher technical risk than grout and lower probability of successful completion. Vitrification, as a supplemental treatment of LAW, has a lower probability of successful implementation as it would be significantly more expensive than the other technologies in both annual and total funding needed.
4. The vitrification and grout alternatives provide long-term protectiveness of human health and the environment and can meet anticipated federal performance standards addressed by the first of the top-tier criteria with high confidence. Some alternatives may be capable of better performance than others, but all can meet existing and anticipated standards.
5. FBSR is a first-of-a-kind technology for the waste chemistry of Hanford LAW and thus, uncertainties in process and waste form performance, cost, and schedule are higher for alternatives using this technology than the grout and vitrification alternatives.
6. Off-site disposal eliminates the concern regarding potential additional impacts to Hanford groundwater and the Columbia River from the on-site disposal of non-vitrified LAW.
7. Off-site disposal at licensed LLW facilities outside of the state of Washington can result in removing ~70% of the inventory of ^{99}Tc, ^{129}I, and nitrates. Evaluation of the projected supplemental LAW feed vectors indicates that when grouted, ~83–93% of the pretreated LAW will meet NRC technical requirements for Class A LLW and waste acceptance criteria at NRC-licensed disposal facilities outside of the state of Washington. The remainder will meet the Class B or C criteria. For the FBSR alternative, ~72% of the waste forms will be Class A, with the remainder meeting the Class B or C criteria.
8. The AEA solely grants authority to DOE to determine whether tank waste is HLW. DOE will classify the Hanford tank waste after retrieval and treatment, in accordance with DOE O 435.1. Out of an abundance of caution, DOE conservatively manages the waste in the Hanford tanks as HLW until retrieval and treatment. The preamble to the RCRA LDR regulations requiring vitrification of HLW makes clear that the intended applicability of the vitrification method is only to the high-activity fraction of tank waste determined to be HLW and not to the low-activity fraction (LAW), and that solidification/stabilization by grout can be an acceptable approach for LAW (55 FR 22626-27).

However, in delegation of RCRA implementation authority to the state of Washington, the state is granted broad discretion over regulatory flexibility and can be more restrictive than federal standards as part of RCRA implementation. In an analogous situation of regulation by multi-agency regulation of DOE and commercial MLLW under RCRA, EPA promulgated a rule providing a conditional exemption from RCRA regulation; the rule grants sole regulatory authority over transportation and off-site disposal of exempted low-level mixed waste (LLMW) to the NRC (66 FR 27217, "Storage, Treatment, Transportation, and Disposal of Mixed Waste").[42]

9. A decision on the supplemental LAW treatment technology is needed as early as possible, and technical maturation activities to be accomplished need to be identified to achieve supplemental LAW treatment operational capability to meet the WTP high-activity fraction processing schedule needs and to accelerate waste storage risk reduction. If the supplemental LAW treatment facility is not ready when needed, tank waste treatment could be delayed, thus extending tank waste storage duration (and resulting in increased storage integrity and waste leakage risks).
10. Detailed evaluation of all six of the high-level criteria according to the taxonomy can be used as a framework for evaluation by decision-making authorities.

6.2 Recommendation(s)

DOE should expeditiously secure and implement multiple pathways for off-site grout solidification/ immobilization and disposal of LAW in parallel with the DFLAW vitrification process.

Recommendation Discussion

Following completion of the assessment of each alternative against top-tier decision Criteria 1 through 4, the FFRDC team sought to use the results of that process to support development of a recommendation using the following framing assumptions:

- In the absence of consensus of the FFRDC team, no recommendation would be made.
- Potential tradeoffs against Criteria 5 and 6 would not be taken into account. Any recommended alternative would reflect the team's consensus highest-value approach, for consideration by DOE and Congress in future negotiations and planning, with respect to the decision factors captured in Criteria 1 through 4.
- Every alternative that survived the screening process was assessed as "moderately effective with moderate uncertainty" or better against Criterion 1. In effect, every alternative was assessed as accomplishing the supplemental LAW treatment mission if successfully completed. As a result, Criterion 1 assessed levels had less influence than Criteria 2 through 4 in determining which alternative, if any, to recommend.
- During the assessment process, the FFRDC team identified additional processing options and variants not included in the defined set of alternatives. A traditional Analysis of Alternatives would restrict any recommendations to the set of fully assessed alternatives. However, the team agreed that it would be acceptable and informative to decision-makers to include a recommendation that may not reflect a fully assessed alternative.

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[42] It is recognized that Washington State has not adopted 40 CFR 266, "Standards for the Management of Specific Hazardous Wastes and Specific Types of Hazardous Waste Management Facilities," Subpart N, "Conditional Exemption for Low-Level Mixed Waste Storage, Treatment, Transportation, and Disposal."

In weighing tradeoffs among criteria, given the assessed qualitative levels for each alternative, the team agreed that the differences in execution schedule among the alternatives, as captured in Criterion 2, should carry the most influence in the selection of a recommended alternative. Differences in probability of successful project completion were assessed as the next-most important differences across the four selected alternatives.

Given these judgments, only Alternatives Grout 4B and Grout 6 were candidates to be the single recommended alternative from the defined list. Comparing these two alternatives, the team considered the benefits of an early start and additional flexibility of future operations for Grout 6, versus a slightly higher probability of success and extra certainty in long-term performance for Grout 4B. The team consensus is that the benefits of the Grout 6 early start and execution flexibility to transition from off-site solidification/immobilization and disposal are decisive. The team chose to recommend the earliest possible initiation of off-site disposition, regardless of whether Alternative Grout 4B or Grout 6 (or a future variant) would be employed to complete the mission. That decision can be made at a later date, with the benefit of experience and technology maturation. The intent of multiple pathways is to provide parallel contractual agreements with multiple facilities for off-site solidification/immobilization and disposal to minimize risks associated with potential facility- or state-specific implementation challenges.

This recommended approach can provide many benefits:

- Provides the capability to achieve the most rapid reduction in the amount of waste stored in the Hanford SSTs and DSTs by using available off-site solidification/immobilization and disposal capacity, and therefore results in the most rapid reduction in risk to human health and the environment attributed to potential future unplanned tank waste releases.
    - DST capacity is available earlier to support waste retrievals and provides greater flexibility for HLW processing options.
    - Earlier available DST capacity provides defense-in-depth for recovery operations if future waste storage tank leaks are identified.
    - This approach can further enable optimized retrieval sequencing to reduce environmental and human health risk most rapidly.
- Provides additional long-term environmental protection, including to the aquifers underlying the Hanford Site and the Columbia River, by disposing of a significant portion of the inventory of risk-driving constituents (e.g., ^{99}Tc, ^{129}I) at off-site facilities that are located in geologic settings with low infiltration and do not have credible pathways to potable water aquifers.
- Provides flexibility in the available treatment technologies and disposal pathways, and reduces the potential for individual choke points to further delay the Hanford tank waste treatment and disposal mission. Concurrent LAW vitrification and solidification/immobilization treatment and disposal pathways would allow LAW routing based on waste characteristics to the most appropriate and efficient treatment technology.
- Mitigates the risk of having LAW with no disposal path by having multiple licensed off-site disposition facilities available to receive Hanford LAW. Further mitigation measures include:
    - Sampling and analyzing the waste first to ensure compatibility with the immobilization process
    - Ensuring that any waste deemed incompatible with the immobilization process is directed to LAW vitrification

  - Ensuring that both off-site permits/permit modifications (if any are needed), and agreements with off-site facilities, are in place prior to initiation of any on-site grouting or any shipment of liquid LAW for off-site treatment/disposal. Such agreements could ideally provide for alternative off-site contingency disposition arrangements in the event that the contracted receiving facility cannot disposition the waste as expected.

  The transport and disposal of liquid LLW has been performed by DOE multiple times, and is not unprecedented (see Volume II, Appendix D, Section D.3.7). In the very unlikely event that both off-site disposal facilities become permanently unavailable, DOE would need to explore several potential approaches, such as: (1) pursue identification of other locations that could accept this waste, (2) continue to work with state regulators and stakeholders to identify viable solutions, and/or (3) pursue application of new and emerging technologies and approaches for disposition of supplemental LAW.

- Enables the rapid start of LAW grout processing and allows time to understand the performance of the DFLAW vitrification process and mature technologies necessary to transition to other disposition approaches for the remaining LAW if desired (e.g., on-site treatment, on-site disposal). For example, a highly instrumented limited pilot demonstration of on-site disposal of grouted LAW, after a decade, could reduce uncertainties of grouted LAW performance and inform future on-site treatment and disposal decisions.
- Provides potential to reduce or eliminate the need for future additional treatment capability and affords time to make such decisions.
- Minimizes financial demands by reducing mission duration and lifecycle costs.
- Offers an approach with high likelihood of successful implementation and mission completion.

This recommendation does not reflect a specific alternative from this analysis because of implementation uncertainties. Elements of specific alternatives were beneficial to inform the alternatives analysis process; however, specific details for implementation of this recommendation will need to be identified through DOE processes, multi-party negotiations, and the NEPA process.

If the recommendation is accepted, the regulatory, stakeholder, and tribal treaty aspects will need to be addressed using established formal processes.

Regulatory Elements

The necessary permits and authorizations will need to be obtained by DOE, including use of the NEPA process to implement the resulting program. Off-site disposal viability was based on review of approved current disposal site waste acceptance criteria and transportation regulations and requirements.

Stakeholder Elements

Stakeholder and community input will be collected and analyzed through DOE's existing agreements, policies, and procedures, including the NEPA process, to inform its decision-making process.

Tribal Treaty Aspects

To address Tribal Nations' treaty rights at the Hanford Site, DOE conducts government-to-government interactions with Tribes and fulfills the trust responsibility of the United States to protect tribal sovereignty and self-determination, tribal lands, assets, resources, and tribal treaty, and other federally recognized and reserved rights, pursuant to DOE O 144.1.

7.0 REFERENCES

10 CFR 962, “Byproduct Material,” *Code of Federal Regulations*, as amended.

40 CFR 261, “Identification and Listing of Hazardous Waste,” *Code of Federal Regulations*, as amended.

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Appendix A. Decision-Informing Criteria

A.1 CRITERIA PROVIDED BY CONGRESS

Section 3125 of the Fiscal Year (FY) 2021 National Defense Authorization Act (NDAA21), directs the U.S. Department of Energy (DOE) to have a Federally Funded Research and Development Center (FFRDC) conduct a follow-on analysis to the analysis required by Section 3134 of the National Defense Authorization Act for FY 2017 (NDAA17) and develop a framework that would help decision-makers decide among treatment technologies for supplemental treatment of Hanford low-activity waste (LAW), associated waste forms, and disposal locations for the waste. This appendix describes the rationale behind the identification of primary decision-informing criteria to be assessed by the FFRDC team, and the details of the taxonomy of subsidiary (lower-tier) criteria and analyses supporting those criteria.

Section 3125 also lists specific factors and criteria that the FFRDC team should address in their assessment of the alternatives. The elements include:

"1. The most effective potential technology for supplemental treatment of LAW that will produce an effective waste form, including an assessment of the:
   a. Maturity and complexity of the technology
   b. Extent of previous use of the technology
   c, Lifecycle costs and duration of use of the technology
   d. Effectiveness of the technology with respect to immobilization
   e. Performance of the technology expected under permanent disposal.

2. The differences among approaches for the supplemental treatment of LAW considered as of the date of the FFRDC team analysis.

3. The compliance of such approaches with the technical standards described in Section 3134(b)(2)(D) of the NDAA17.

4. The differences among potential disposal sites for the waste form produced through such treatment, including mitigation of radionuclides, including technetium-99, selenium-79, and iodine-129, on a system level.

5. Potential modifications to the design of facilities to enhance performance with respect to disposal of the waste form to account for the following:
   a. Regulatory compliance
   b. Public acceptance
   c. Cost
   d. Safety
   e. The expected radiation dose to maximally exposed individuals over time
   f. Differences among disposal environments.

6. Approximately how much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals to reduce disposal costs for radionuclides described in item 4 above.

7. Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level by the performance assessment of a potential disposal site and, if the radionuclides cannot be left in the waste form, how to account for the secondary waste stream.

8. Other relevant factors relating to the technology […], including the following:
   a. The costs and risks in delays with respect to tank performance over time
   b. Consideration of experience with treatment methods at other sites and commercial facilities
   c. Outcomes of the Test Bed Initiative of the DOE Office of Environmental Management at the Hanford Nuclear Reservation."

In terms of stakeholder values, these elements include a mix of fundamental goals (e.g., safety and effectiveness with respect to immobilization), types of evidence (e.g., extent of previous use, findings from the Test Bed Initiative, and experience with treatment methods at other sites), and contributing risk factors (e.g., expected dose and differences among disposal sites).

A.2 SELECTION CRITERIA TEMPLATE

The following criteria were developed for review of the alternatives.

Decision-Informing Criteria Assessment Template

1. Long-term effectiveness
(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion
Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply were screened out.

1.1.1. Residual toxicity of wastes

1.1.1.1. Nitrates/nitrites

1.1.1.2. RCRA metals: No reduction in inherent toxicity; No measure of effectiveness (MOE) needed since all are equivalent.

1.1.1.3. LDR organics:

1.1.1.4. Ammonia

1.1.1.5. Greenhouse gas emissions
No expected difference in residual carbon footprint across alternatives.

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
MOE: Estimated concentration over ~1,000 years (to DOE O 435.1); delay to peak is when peak occurs and differs between scenarios; identify peak to 10,000 years for information only (i.e., compliance vs. post-compliance periods).

1.1.2.1.1. Iodine

1.1.2.1.2. Technetium-99 (^{99}Tc)

1.1.2.1.3. Selenium-79 (^{79}Se)

1.1.2.1.4. Cesium and strontium
Cesium and strontium half-lives make them a pre-completion issue; no MOE needed here.

1.1.2.2. Nitrates/nitrites

1.1.2.3. Ammonia

1.1.2.4. RCRA metals
MOE: Leachate Toxicity Characteristic Leaching Procedure (TCLP) compliance.

1.1.2.4.1. Mercury

1.1.2.4.2. Chromium

1.1.2.4.3. Other

1.1.3. Total volume of primary and secondary waste forms

1.2. Long-term risks upon successful completion

MOE: Error bars in 1.1. Estimates above vs. margin under health/regulatory standards.

1.2.1. Confidence in estimated residual toxicity

- 1.2.1.1. LDR organics/destruction of organics
- 1.2.1.2. Nitrates/nitrites
- 1.2.1.3. Ammonia/ammonium ion.
- 1.2.1.4. RCRA metals
  - 1.2.1.4.1. Mercury
  - 1.2.1.4.2. Chromium
  - 1.2.1.4.3. Other RCRA metals

1.2.2. Confidence in immobilization with regard to groundwater

- 1.2.2.1. Iodine
- 1.2.2.2. Technetium (including non-pertechnetates)
- 1.2.2.3. ^{79}Se
- 1.2.2.4. Nitrates/nitrites
- 1.2.2.5. Ammonia/ammonium ion
- 1.2.2.6. RCRA metals
  - 1.2.2.6.1. Mercury
  - 1.2.2.6.2. Chromium
  - 1.2.2.6.3. Other RCRA metals

1.2.3. Confidence in total volume of primary and secondary waste forms produced

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

- 2.2.1.1. Radiation
- 2.2.1.2. Chemical exposure
- 2.2.1.3. Particulate exposure
- 2.2.1.4. Physical injury

2.2.2. Transportation risks

MOE: Number and distance of trips, health risks of material being transported.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

- 2.3.2. Atmospheric discharges
- 2.3.3. Transfer/process tank (on-site) spills
- 2.3.4. Off-site transportation spills
- 2.3.5. Secondary waste streams generated
- 2.3.6. Greenhouse gas emissions

2.4. Duration

- 2.4.1. Duration to hot startup (years from decision)
- 2.4.2. Duration to full capacity (additional years)
- 2.4.3. Duration of operations (additional years)
- 2.4.4. Risk of additional mission delay
  - 2.4.4.1. Delay due to technical/engineering issues
  - 2.4.4.2. Delay due to annual operating costs exceeding budget

3. Likelihood of successful mission completion (including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

- 3.1.1. Technology and engineering risks of things that would stop the project before completion
  - 3.1.1.1. Technology/engineering failure modes (alternative-specific)
    - 3.1.1.1.1. [Failure mode #1 with likelihood]
    - 3.1.1.1.2. [Failure mode #2 with likelihood]
    - 3.1.1.1.3. [Failure mode #3 with likelihood]
    - 3.1.1.1.4. …
  - 3.1.1.2. Process complexity
    Considers static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, required chemicals added, etc.
    - 3.1.1.2.1. Unit operations (alternative-specific)
    - 3.1.1.2.2. Accuracy of controls needed
    - 3.1.1.2.3. Commercially available/“of a type”/bespoke systems
    - 3.1.1.2.4. Overall flowsheet integration complexity
  - 3.1.1.3. Required facilities/infrastructure
  - 3.1.1.4. Required demolition/removal/modification
  - 3.1.1.5. Technology maturity (including Test Bed Initiative)

    MOE: Technology readiness levels for critical technology elements.
    MOE: Demonstrated effectiveness elsewhere (including Test Bed Initiative).
    MOE: Analogous DOE experience.
- 3.1.2. Robustness to known technical risks
  (ability to recover from failure modes listed above)
  - 3.1.2.1. Process and equipment robustness

3.1.2.2. Recovery from unexpectedly poor waste form performance

3.1.3. Adaptability to the full range of tank waste compositions

3.1.4. Potential to incorporate future technology advances

3.2. Likelihood and consequences of failing to complete due to resource constraints

3.2.1. MOE: Average annual spending vs. benchmark budget.

3.2.2. MOE: Projected peak spending vs. benchmark budget.

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget
MOE: Ability to start and stop operations in response to external factors.

3.2.4. Expected work remaining at failure point

3.2.5. Worst case (plausible) work remaining at failure

3.3. Likelihood and consequences of failing to complete due to unavailability of key services or materials

4. Lifecycle Costs
(discounted present value)

4.1. Capital project costs (Design plus facility construction and cold commissioning)

4.2. Operations costs

4.3. Shutdown and decommissioning costs

5. Securing and Maintaining Necessary Permits/Authorities
(regulatory approval)

6. Community/Public Acceptance (state, local)

With respect to Criteria 5 and 6, the FFRDC team concluded that the public should have the benefit of this and other analyses (e.g., by National Academy of Sciences, Engineering, and Medicine [NASEM] and U.S. Government Accountability Office [GAO]) prior to formulating their inputs to the decision-making process. Likewise, securing regulatory approval is part of the negotiation process between government agencies, and it would be inappropriate for the FFRDC team to estimate the likelihood of specific outcomes. These criteria are included in the taxonomy for completeness but were not assessed as part of the evaluations of individual alternatives. However, where there are significant observations, issues, or uncertainties with respect to Criteria 1 through 4 of the Assessment Template that are potentially relevant to regulation or stakeholder acceptance of specific alternatives, these are addressed in the accompanying discussion of that alternative in Volume II, Appendix C and Appendix E.

A.3 REFERENCES

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Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.

Appendix B. Summary of Selection Criteria Data for Four Selected Alternatives

B.1 INTRODUCTION

This appendix provides summaries of the following four alternatives discussed in Section 3.0 of the report:

- **Vitrification 1** – Vitrification with on-site disposal at Hanford
- **FBSR 1A** – Fluidized bed steam reformed solid monolith product with on-site disposal at Hanford
- **Grout 4B** – Grouting performed by an off-site vendor with off-site disposal
- **Grout 6** – Phased off-site grouting and disposal, then on-site grouting and disposal in containers.

This appendix is a shortened version of the full Alternative Selection Criteria provided in Volume II, Appendix D for these four alternatives. It is not intended to replace the full Alternative Selection Criteria but is provided as a version that is easier to compare between alternatives. The text for each description is derived from but not identical to the longer criteria sections.

In the tables below, the green descriptors indicate a positive attribute of that alternative, the red descriptors indicate a negative attribute of the alternative. The few brown descriptors are items that are not negative attributes at this time, but could become a negative attribute, depending on the outcome of future activities.

Volume II, Appendix C provides an overview of each of the technologies and their assumptions, with schematics depicting the building blocks of each alternative.

B.1.1 Alternative Vitrification 1, Single Supplemental Low-Activity Waste Vitrification Plant

Alternative Vitrification 1		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite are destroyed in the melter/offgas system. There is some uncertainty about the residual toxicity/long-term performance of secondary wastes.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Large amount of ammonia from melter reactions is present in the secondary waste disposed of at the Integrated Disposal Facility (IDF) in a grout waste form and its long-term behavior is not well understood. ^{129}I is semi-volatile and its partitioning to the secondary streams and performance in secondary wastes after disposal in IDF carries moderate uncertainty. There is low mobility of radionuclides and hazardous metals in the glass waste form with respect to groundwater.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste form is smallest. Total volume of secondary liquid waste is largest; likely requiring expansion of the Effluent Treatment Facility (ETF). Largest volume of secondary solid waste.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	Expect destruction of most organics in the waste by melter/plenum. There is uncertainty in the organic speciation and behavior during vitrification and the quantity of hazardous organics produced by the melter (e.g., acetonitrile) and their fate in downstream processing. Mercury – Low confidence that partitioning will be as expected; mercury is highly volatile and notoriously distributed in multiple offgas system components. High confidence that most Resource Conservation and Recovery Act (RCRA) metals (except mercury) are mostly retained in glass waste form by recycling the offgas condensate.

Alternative Vitrification 1		
	1.2.2 Confidence in immobilization with regard to groundwater	Low confidence in ^{129}I speciation/partitioning/retention in secondary wastes. High confidence in technetium partitioning during operations and level of retention in glass. Uncertainty of ^{99}Tc behavior during melter idling where it extensively vaporizes and distributes to the offgas system components. High confidence in low groundwater impact of ^{129}I or ^{99}Tc from disposed primary waste in IDF due to stability of glass waste form. Moderate uncertainty in ^{129}I and ^{99}Tc long-term immobilization in stabilized secondary wastes with or without getters (for iodine) are used. High confidence in nitrate/nitrite destruction. Low confidence in ammonia behavior in grouted secondary waste. High confidence in immobilization and limited impact to groundwater for all contaminants of concern (CoC) during the 1,000-year compliance period based on contemporary assessments.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in volume of primary waste form. Moderate confidence in secondary waste form volume.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Delayed start-up of processing due to high costs and complex construction, which will delay retrieval of wastes from tanks, allowing more time for further degradation and potential future leaks. Consumption of entire budget would prevent early start up or alternate processing.
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Challenging to mitigate risk of contamination due to volatility of radionuclides and hazardous species that distribute to offgas components, high maintenance requirements, and fly-wheeling of radionuclides. Challenging to mitigate risk of chemical exposure: high maintenance requirements of melter and offgas system, hazardous chemicals (e.g., liquid ammonia), resulting in 38 high-hazard consequences for workers identified. Two medium consequence public hazards.
	2.2.2 Transportation risks	Low transportation risks.
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	High volume of wastewater discharges likely requiring new/expanded ETF. ^{129}I fate in offgas and secondary wastes is unconfirmed.
	2.3.2 Atmospheric discharges	High atmospheric discharges (38 MT constituents of potential concern [CoPC] per 1 Mgal of waste treated).
	2.3.3 Transfer/process tank (on-site) spills	Low on-site and off-site transportation spills.
	2.3.4 Off-site transportation spills	Low risk.
	2.3.5 Secondary waste streams generated	High quantity of secondary waste streams generated.
	2.3.6 Greenhouse gas emissions	High greenhouse gas emissions (1.5 Mgal fuel, 74 GWh electricity, and 570 deliveries per 1 Mgal of waste treated).

Alternative Vitrification 1		
2.4 Duration	2.4.1 Duration to hot startup	Expect ~25 years to construct.
	2.4.2 Duration to full capacity	Expect 3 years to ramp up all melters to capacity.
	2.4.3 Duration of operations	Extended duration due to late start and slow ramp up to full capacity.
	2.4.4 Risk of additional delay	Moderate risk of delay due to technical issues due to mitigation based on lessons learned from first low-activity waste (LAW) melters. High risk of delay due to annual operating costs exceeding budget.
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Low likelihood of failure – First LAW melters will inform design/operations. Low risk of failure to corrosion, fire, release of radionuclides, control of the wet electrostatic precipitator (WESP). Highly complex and integrated system causing operation challenges. Extensive controls needed – Sampling/analysis, modeling. Many one-of-a-kind components. High overall flowsheet integration complexity. High number of required facilities/infrastructure/chemicals/utilities. Demonstrated effectiveness of Waste Treatment and Immobilization Plant (WTP) LAW melters will inform design/operations.
	3.1.2 Robustness to known technical risks	Robustness/adaptability – First LAW melters will inform design and operations, mitigating risk by the time the supplemental LAW melters begin operations.
	3.1.3 Adaptability to a range of waste compositions	Ability to adjust waste loading and glass-forming chemical recipe would permit adaptability.
	3.1.4 Ability to incorporate future advances	High capital cost and unique operations make incorporation of future advances challenging.
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding needs would likely exceed the annual benchmark funding level.
	3.2.2 Projected peak spending	Peak funding needs would likely greatly exceed the annual benchmark funding level.
	3.2.3 Schedule flexibility	Low schedule flexibility; melters have limited ability to operate at varying rates due to need to maintain cold cap coverage.
	3.2.4 Expected work remaining at failure point	Unlikely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Unlikely that sufficient funds would be available to start up by need date.
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Numerous one-of-a-kind components and materials would be challenging to maintain over the extended operating life cycle duration. Extensive sample characterization may exceed analysis capacity and delay processing.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$12,700 M

B.1.2 Alternative FBSR 1A, Fluidized Bed Steam Reforming Onsite Disposal

Alternative FBSR 1A		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite and Land Disposal Restrictions (LDR) organics destroyed. Residual toxicity of secondary wastes – Mercury on granular activated carbon (GAC). No ammonia in final waste form. Iodine and technetium partition predominantly to primary waste.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Low release of technetium and metals from granular product if structural incorporation occurs. Iodine performance in final waste form appears to be similar to technetium; however, there is greater uncertainty with long-term mobility reduction and uncertainties in structural incorporation.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is intermediate (~1.0×, including ~10% coal). No secondary liquid waste.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	Destruction of all organics in denitration and mineralizing reformer (DMR) and/or thermal oxidizer (TO). Mercury – High confidence of partitioning to GAC. Moderate – High confidence in iodine partitioning to primary waste form. High confidence technetium and most RCRA metals are retained in granular product. High confidence non-pertechnetate destroyed and retained in granular product. High confidence in nitrate/nitrite destruction; no ammonia issues.
	1.2.2 Confidence in immobilization with regard to groundwater	High confidence in low groundwater impact of ^{129}I or ^{99}Tc and moderate-high confidence of ^{129}I IDF performance with projected incorporation and likely retention in and stability of the granular mineral product primary waste form; however, moderate uncertainty on the degree of incorporation. High confidence in nitrate/nitrite and ammonia destruction. High confidence in immobilization and limited impact to groundwater for all CoCs during the 1,000-year compliance period based on contemporary assessments.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in total volume of primary and secondary waste forms.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Delayed start-up of processing due to high costs and complex construction, which would delay retrieval of wastes from tanks, allowing more time for further degradation and potential future leaks. Consumption of entire budget would prevent early startup or alternate processing.
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Multiple hazards; 34 high-consequence worker hazards. One medium consequence public hazard. High risk of contamination from radioactive dust during maintenance. High risk of chemical exposure: high maintenance requirements. Hazardous chemicals, cryogenic liquids; steam.
	2.2.2 Transportation risks	Low transportation risks.

Alternative FBSR 1A		
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	No wastewater discharges.
	2.3.2 Atmospheric discharges	Moderate-low atmospheric discharges (4 MT CoPCs per 1 Mgal waste treated).
	2.3.3 Transfer/process tank (on-site) spills	Low on-site transportation spills.
	2.3.4 Off-site transportation spills	Low off-site transportation spills.
	2.3.5 Secondary waste streams generated	Low amount of secondary waste streams generated.
	2.3.6 Greenhouse gas emissions	High greenhouse gas (200,000 gal fuel, 984 MT coal, 19 GWh, 416 deliveries per 1 Mgal waste treated).
2.4 Duration	2.4.1 Duration to hot startup	Expect ~15 years to construct. No potential for early start.
	2.4.2 Duration to full capacity	Expect 3 years to ramp up both units to capacity.
	2.4.3 Duration of operations	Delay to high-level waste (HLW) campaign because of slow/late startup of fluidized bed steam reforming (FBSR).
	2.4.4 Risk of additional delay	High risk of additional delay due to technical issues.
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Moderate likelihood of failure – Fully integrated offgas system untested – baseline process moderate maturity with this waste/waste form. Low expected release of radionuclides – Not volatized. Highly complex and integrated system causing operation challenges. Extensive controls needed – Sampling/analysis, modeling. Several one-of-a-kind components. High overall flowsheet integration complexity. High number of required facilities/infrastructure/chemicals/utilities. Demonstrated effectiveness – First-of-a-kind for similar waste form.
	3.1.2 Robustness to known technical risks	Low robustness. Potential for delays.
	3.1.3 Adaptability to a range of waste compositions	Moderate adaptability.
	3.1.4 Ability to incorporate future advances	Challenging for redesign or process changes.
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding needs would likely exceed the annual benchmark funding level.
	3.2.2 Projected peak spending	Peak funding needs would likely greatly exceed the annual benchmark funding level.
	3.2.3 Schedule flexibility	Moderate schedule flexibility.
	3.2.4 Expected work remaining at failure point	Unlikely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Unlikely that sufficient funds would be available to start up by need date.

Alternative FBSR 1A		
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Numerous one-of-a-kind components and materials. Single U.S. company technology supplier.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$5,527 M

B.1.3 Alternative Grout 4B, Off-site Vendor for Grouting with Off-site Disposal

Alternative Grout 4B		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite not destroyed (but inconsequential to off-site disposal). Treatment, if needed, lowers LDR organics in final waste form to beneath limits; volatile organics in secondary liquid waste treatable in ETF. Minimal ammonia in primary or secondary waste forms.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Off-site disposal does not have a pathway to potable water due to geology.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is largest (1.8×). Secondary liquid volume from evaporator to ETF is moderate.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	High confidence in absence or removal of all organics by evaporation/oxidation, if needed. High confidence in no change to toxicity of nitrate/nitrite and RCRA metals. High confidence ammonia would not be significant in grouted tank waste.
	1.2.2 Confidence in immobilization with regard to groundwater	Mercury – High confidence in ability to sequester in grout waste form. High confidence most RCRA metals are retained in grout waste form. No impact of inventory and behavior of technetium, non-pertechnetate, or iodine on Hanford groundwater. High confidence off-site disposal does not have a pathway to potable water due to geology.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in predicted total of primary waste form (1.8×) and secondary liquid (~0.4×) waste and solid secondary waste form volume.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Lowest risk of additional tank leaks; HLW and retrievals could meet schedules. Alternative does not consume entire budget, providing opportunity for early start as part of hybrid or concurrent alternatives. High flexibility in tank utilization, transfer piping.

Alternative Grout 4B		
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Low risk of contamination: no volatile radionuclides, low maintenance. Low risk of chemical exposure: low maintenance requirements. Minimal hazardous chemicals, zero high-hazard consequences for workers; 12 medium consequence worker hazards.
	2.2.2 Transportation risks	Moderate risk; high number of radioactive transports.
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	Moderate amount of wastewater discharges (~0.4×), no new ETF needed. Minimal solid, moderate liquid secondary waste streams generated.
	2.3.2 Atmospheric discharges	Negligible atmospheric discharges of radionuclides or CoPCs.
	2.3.3 Transfer/process tank (on-site) spills	Low on-site transportation spill risk.
	2.3.4 Off-site transportation spills	Low off-site transportation spill risk.
	2.3.5 Secondary waste streams generated	Minimal secondary wastes generated.
	2.3.6 Greenhouse gas emissions	~30,000 gal fuel oil for evaporator boiler, 2.5 GWh electricity, 209 deliveries per 1 Mgal treated.
2.4 Duration	2.4.1 Duration to hot startup	Expect ~5 years (including construction of evaporator).
	2.4.2 Duration to full capacity	Vendors are available with immobilization capacity.
	2.4.3 Duration of operations	As needed to support HLW mission.
	2.4.4 Risk of additional delay	Minimal risk of delay (potential early start as part of hybrid; see alternative Grout 6).
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Low likelihood that LDR organics are above limits or removal is inadequate. Minimal process complexity and integration. Minimal controls needed – Sampling/analysis, modeling. Commonly available components/equipment. Low overall flowsheet integration complexity. Low number of required facilities/infrastructure/chemicals/utilities. Cross-site supernate transfer line not needed to support this alternative. Demonstrated effectiveness with Hanford waste and off-site disposal in Test Bed Initiative.
	3.1.2 Robustness to known technical risks	High robustness/adaptability – Other site experience 20+ years.
	3.1.3 Adaptability to a range of waste compositions	High adaptability to accommodate feed variability. Alternative is to divert incompatible waste to WTP LAW vitrification.
	3.1.4 Ability to incorporate future advances	Readily incorporate future advances. Vendors are anticipated to have sufficient capacity, or could expand if needed, to meet demand (although some may require permit changes).

Alternative Grout 4B		
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding needs would likely be well beneath the annual benchmark funding level. Likely that sufficient funds would be available to start up by need date.
	3.2.2 Projected peak spending	Peak funding needs would likely be well beneath the benchmark funding level.
	3.2.3 Schedule flexibility	Flexible process (e.g., simple shutdown, common construction methods).
	3.2.4 Expected work remaining at failure point	Likely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Likely that sufficient funds would be available to start up by need date.
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Grout production currently available from vendor(s). Disposal sites available (although only one for U.S. Nuclear Regulatory Commission [NRC] low-level waste [LLW] Class >A). Alternative sources of key materials may need development in long term.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$3,854 M

B.1.4 Alternative Grout 6, Phased Off-site and On-site Grouting in Containers

Alternative Grout 6		
1. Long-term effectiveness (environmental and safety risk after disposal)		
1.1 Residual threat to health and environment upon successful completion	1.1.1 Residual toxicity of wastes	Nitrate/nitrite not destroyed (inconsequential during off-site disposal). If present, pretreatment lowers LDR organics in final waste form to beneath limits. Minimal ammonia in primary or secondary waste.
	1.1.2 Mobility of primary and secondary wastes to a groundwater source	Phases 1–2 (off-site disposal): Off-site disposal does not have a pathway to potable water due to geology. Phase 3 (on-site disposal): Getter for iodine (or vault disposal) and reduced inventory of iodine and technetium disposed of onsite expected to provide long-term mobility reduction.
	1.1.3 Total volume of primary and secondary waste forms	Total volume of primary waste is large (1.8×). Secondary liquid volume from evaporator to ETF is moderate. Very low secondary solid waste.
1.2 Long-term risks upon successful completion	1.2.1 Confidence in estimated residual toxicity	Low uncertainty in absence or removal of all organics by evaporation/oxidation, if needed. High confidence in no change to toxicity of nitrate/nitrite and RCRA metals. High confidence ammonia would not be significant in grouted tank waste. High confidence organics in secondary liquid waste absent or treatable.

Alternative Grout 6		
	1.2.2 Confidence in immobilization with regard to groundwater	Mercury – High confidence in ability to sequester in grout waste form. High confidence most RCRA metals are retained in grout waste form. Phases 1–2: No impact of inventory and behavior of technetium, non-pertechnetate, or iodine. High confidence off-site disposal does not have a pathway to potable water due to geology. Phase 3: High confidence in immobilization and limited impact to groundwater for all CoCs during the 1,000-year compliance period based on contemporary assessments. Moderate confidence in iodine getter performance beyond compliance period and long-term performance of grout.
	1.2.3 Confidence in total volume of primary and secondary waste forms produced	High confidence in predicted total of primary waste form (1.8×) and secondary liquid (~0.4×) waste and solid secondary waste volume.
2. Implementation schedule and risks (environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)		
2.1 Specific risks or benefits related to ongoing tank degradation		Lowest risk of additional tank leaks; HLW and retrievals could meet schedules. Alternative is intended to consume entire budget, enabling early start and thereby reducing risk of leaks. Flexibility in tank utilization, transfer piping.
2.2 Risks to Humans (other than tank degradation)	2.2.1 Effort required to ensure worker safety	Low risk of contamination: no volatile radionuclides, low maintenance. Low risk of chemical exposure: low maintenance requirements. Minimal hazardous chemicals, zero high-hazard consequences for workers; 12 medium consequence worker hazards.
	2.2.2 Transportation risks	Moderate risk; high number of radioactive transports.
2.3 Risks to the Environment (other than tank degradation)	2.3.1 Wastewater discharges	Moderate amount of wastewater discharges (~0.4×), no new ETF needed. Minimal solid, moderate liquid secondary waste streams generated.
	2.3.2 Atmospheric discharges	Negligible atmospheric discharges of radionuclides or CoPCs.
	2.3.3 Transfer/process tank (on-site) spills	Low on-site transportation spill risk.
	2.3.4 Off-site transportation spills	Low off-site transportation spill risk.
	2.3.5 Secondary waste streams generated	Minimal secondary wastes generated.
	2.3.6 Greenhouse gas emissions	~30,000 gal fuel oil for evaporator boiler, 2.5 GWh electricity, 209 deliveries per 1 Mgal treated.
2.4 Duration	2.4.1 Duration to hot startup	Expect ~5 years to start up (including construction of evaporator) for Phase 1.
	2.4.2 Duration to full capacity	Vendors are available with immobilization capacity for Phase 1.
	2.4.3 Duration of operations	As needed to support HLW mission for Phases 2–3.
	2.4.4 Risk of additional delay	Minimal risk of delay.

Alternative Grout 6		
3 Likelihood of successful mission completion (including technical, engineering, and resource-related risks)		
3.1 Likelihood & consequences of failing to complete for technical reasons	3.1.1 Technology and engineering risk	Low likelihood that LDR organics are above limits or that removal inadequate, if needed. Minimal process complexity and integration. Minimal controls needed – Sampling/analysis, modeling. Commonly available components/equipment. Low overall flowsheet integration complexity. Low number of required facilities/infrastructure/chemicals/utilities. Cross-site supernate transfer line not needed to support this alternative. Demonstrated effectiveness for Phase 1 with Hanford waste and off-site disposal in Test Bed Initiative.
	3.1.2 Robustness to known technical risks	High robustness/adaptability – Other site experience 20+ years.
	3.1.3 Adaptability to a range of waste compositions	High adaptability to accommodate feed variability. Alternative is to divert incompatible waste to WTP LAW vitrification.
	3.1.4 Ability to incorporate future advances	Readily incorporate future advances. Vendors are anticipated to have sufficient capacity or could expand capacity, if needed, to meet demand (although some may require permit changes).
3.2 Likelihood & consequences of failing to complete due to resource constraints	3.2.1 Annual average spending	Funding intended to match the annual spending benchmark. Likely that sufficient funds would be available to start up by need date.
	3.2.2 Projected peak spending	Peak funding needs would likely be within the annual benchmark funding level.
	3.2.3 Schedule flexibility	Flexible process (e.g., simple shutdown, common construction methods).
	3.2.4 Expected work remaining at failure point	Likely that sufficient funds would be available to start up by need date.
	3.2.5 Worst plausible case work remaining at failure	Likely that sufficient funds would be available to start up by need date.
3.3 Likelihood and consequences of failing to complete due to unavailability of key services and materials		Grout production currently available from vendors. Disposal sites available (only one for NRC LLW Class >A) for Phases 1-2. Alternative sources of key materials may need development in long term.
4. Life Cycle Costs (discounted present value)		
Total	(discounted)	$4,127 M

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Appendix C. Selection Criteria Assessments for Four Selected Alternatives

C.1 INTRODUCTION

The decision-informing criteria described in Volume I, Appendix A were developed as assessment measures for the alternatives evaluated in this report. Each alternative was assessed against the criteria by a sub-team of subject matter experts on the Federally Funded Research and Development Center (FFRDC) team. Where applicable, this expert team reviewed previously developed technical reports to identify information to support each assessment. In the absence of specific technical information regarding specific criteria, expert judgement from related work and experience was used to inform the assessment.

C.2 SELECTION CRITERIA ASSESSMENTS – FOUR SELECTED ALTERNATIVES

The criteria for each alternative were reviewed by the team, and the results were documented. The detailed results are included in this appendix for four of the 15 alternatives that were fully evaluated. Volume II, Appendix D provides the selection criteria assessments of all 15 alternatives.

C.2.1 Selection Criteria Assessment for Alternative Vitrification 1

Alternative Vitrification 1:

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. *Residual threat to health and environment upon successful completion*

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – all retained – amount increased by treatment.]

1.1.1.1. Nitrates/nitrites – Low residual toxicity. Nitrate/nitrite are nearly completely destroyed by vitrification and offgas processes – small residuals in caustic scrub solution that is sent to the Effluent Treatment Facility (ETF) and end up grouted for disposal in the Integrated Disposal Facility (IDF).

1.1.1.2. RCRA metals – High residual toxicity. RCRA metals are contained in the primary waste form except mercury. Final partitioning of mercury has high uncertainty. All primary offgas components will have mercury contamination and secondary offgas components will have mercury contamination up to the granular activated carbon (GAC). Mercury captured on the GAC will be micro-encapsulated in grout. Some mercury will partition to the Liquid Effluent Retention Facility (LERF)/ETF and end up in a grouted waste form disposed of in IDF. No destruction; mercury is vaporized to secondary stream.

1.1.1.3. Land Disposal Restrictions (LDR) organics – Low Residual toxicity. Most organics are destroyed by the vitrification and secondary offgas processes. Some organics generated by incomplete combustion of sugar would be captured in the submerged bed scrubber (SBS) condensate and partitioned to LERF/ETF for destruction. Some organics will be captured by the GAC and grouted for disposal in IDF. Organics in waste largely destroyed, whereas melter produces some; remaining organics partition to secondary waste and are destroyed or sequestered in subsequent treatment; if planned disposition is found inadequate, it is assumed that changes would be made to processes to be within regulatory requirements.

1.1.1.4. Ammonia – High residual toxicity. The vitrification process generates ammonia that will be partitioned to the LERF/ETF for treatment. In addition, ammonia is added to the secondary offgas system (to destroy NO_x) and emitted from the vitrification facility stack. Ammonia in ETF will be precipitated and incorporated into a grout waste form disposed of in IDF with unknown long-term behavior.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
[MOE: Estimated peak groundwater concentration at IDF Performance Assessment (PA) compliance point over ~1,000 years (to DOE O 435.1, *Radioactive Waste Management*; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period) (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

1.1.2.1.1. Iodine – Iodine is expected to partition predominately to solid and liquid secondary wastes (liquid/solid/gas). Release rates for some macroencapsulated components (solid secondary waste, e.g., GAC) expected to be higher than microencapsulation of iodine in liquid secondary waste grout from ETF; both are disposed of in IDF (without getters) but improvements to primary waste form could be applied to secondary wastes.

1.1.2.1.2. Technetium (non-pertechnetate is evaluated in Section 1.2.2.2) – Most (~99%) ^{99}Tc assumed to be retained in the primary waste form – and 2017 IDF PA predicted low-activity waste (LAW) glass contribution to be 10× lower than compliance limit. A small fraction will be captured on the high-efficiency particulate air (HEPA) filters, which are crushed and macroencapsulated in grout. Leach rates from the spent HEPAs is evaluated in the current PA but predicted quantities of technetium on HEPA filters are assumed to be extremely low but do not accurately account for system full performance.

1.1.2.1.3. Selenium-79 (^{79}Se) – Uncertainty in partitioning due to volatility. Like ^{99}Tc, a small portion could be captured on the spent HEPA filters that are microencapsulated and disposed of in IDF. Low inventory of ^{79}Se (114 Ci, see Volume II, Section E.3.1.3) leads to minimal risk to drinking water.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites. N/A – Destroyed in melter with small amount of nitrate produced and present in the ETF liquid secondary waste, and IDF PA risk budget tool showed peak concentrations 10× below on drinking water standards.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives.] – Ammonia is generated by the melter process (when sugar used as a reductant) and is also added during secondary offgas treatment to destroy NO_x. Ammonia from the melter process is typically partitioned to LERF/ETF while excess ammonia added during secondary offgas treatment is exhausted from the vitrification facility stack. Ammonia will also be present from first LAW melter system so its presence at ETF is not differentiating among alternatives. Ammonia in ETF is precipitated and encapsulated in grout waste form disposed of in IDF. Release from waste form at some TBD rate either during production, curing, or disposal is likely.

1.1.2.4. RCRA metals – [MOE is leachate Toxicity Characteristic Leaching Procedure (TCLP) compliance.] Leach rates of RCRA metals from the glass are predicted to be very low and expected to pass TCLP.

1.1.2.4.1. Mercury – [MOE is retention of mercury in primary vs. secondary waste form.] Mercury will not be retained in glass and will end up in a grouted waste form for all options. For vitrification, the mercury will be portioned throughout the secondary wastes, with most presumed to be on the activated carbon bed.

1.1.2.4.2. Chromium – [MOE is retention of chromium in waste form.] Chromium will be captured in the primary waste form and leach rate dependent on the dissolution rate of the glass. Like technetium, a small fraction could be partitioned to the spent HEPA filters that are macroencapsulated in grout and disposed of in IDF.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals (e.g., lead) appear not to exceed Drinking Water Standards (DWS) limits and are significantly beneath concentration of chromium.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – For 1 gallon of LAW feed: 0.34 gallons of primary waste glass, 0.05 gallons of spent equipment, 0.05 of grouted solids from ETF, and 1.8 gallons of liquid effluent disposed of at a state-approved land disposal site (SALDS). (Note: Flush volumes not included in water effluent totals) (RPP-RPT-63328, *Calculating the Non-Monetary Impact of Operating a Vitrification Facility*).

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Destruction of organics. High uncertainty exists in the speciation of the organics in the waste feed; the amount and speciation of organics that will be vaporized, destroyed, or produced by the melter and scrubbed from the offgas in the primary offgas system and subsequently sent to LERF/ETF; and the amount and type of organics that will be captured on the GAC, which is microencapsulated and disposed of in IDF.

1.2.1.2. Nitrates/nitrites – High confidence that nitrate and nitrite will be nearly completely destroyed by the immobilization process.

1.2.1.3. Ammonia/ammonium ion – Moderate risk. None in primary waste form. Ammonia in secondary liquid waste treated at LERF/ETF and will be in the immobilized waste form disposed of in IDF.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – Moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – Moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine – Moderate confidence overall. Low confidence that partitioning of iodine through process will proceed as expected and what resulting speciation will be. High confidence that the amount of iodine in secondary wastes will be higher than assumed in IDF PA. Partitioning significantly impacted if melter idles frequently. Any iodine retained in glass will have low leach rates dependent on glass stability. Low confidence in the immobilization of iodine in either stabilized solid secondary waste (e.g., GAC) or stabilized liquid secondary wastes assuming no getter used in secondary waste grout. Iodine is a key constituent of interest in the IDF PA. ^{129}I can define waste classification but concentrations in secondary wastes are lower than the U.S. Nuclear Regulatory Commission (NRC) low-level waste (LLW) Class A limit[1]. Once released by chemical reactions and leached into the subsurface there is limited to no natural attenuation of iodide, and as such the secondary waste iodine inventory could impact groundwater compliance limits. Mitigated during the compliance period by low rate of water to transport.

1.2.2.2. Technetium (including non-pertechnetates) – Moderate confidence overall. High confidence that partitioning of technetium through process will proceed as expected, including non-pertechnetate (converts to pertechnetate in melter). (Note: It is also expected that the amount of ^{99}Tc in secondary wastes will be higher than assumed in IDF PA due to model simplifications that did not incorporate all known impacts on ^{99}Tc partitioning.) Partitioning to offgas is significantly impacted if melter idles frequently or wet electrostatic precipitator (WESP) deluge frequency/time is higher than expected or if its scrubbing efficiency is lower than expected. Any ^{99}Tc in the primary glass waste form will have leach rate dictated by stability of the glass. Within the grouted secondary waste form, there is high confidence that technetium will be reduced and insoluble technetium. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form can be destabilized with time due to oxidation but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA.

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[1] ^{129}I is listed in Table 1 of 10 CFR 61.55 *Waste Classification*, that is used to classify wastes for near-surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

Technetium can define waste classification and concentrations may approach the Class A limit[2]. Once in the subsurface, there is limited to no natural attenuation of technetium, and as such the secondary waste grout technetium inventory could impact groundwater compliance limit.

1.2.2.3. ^{79}Se – High confidence in minimal risk. Limited to no data to date on the partitioning in Waste Treatment and Immobilization Plant (WTP) and mobility within grout waste forms. ^{79}Se is a RCRA metal (as selenium) but only a small inventory across the Hanford tanks (2 kg) may reach the secondary waste. Selenium has limited attenuation in the Hanford subsurface. The limited inventory may minimize overall risk to groundwater. Mitigated during the compliance period by minimal water infiltration thru vadose zone.

1.2.2.4. Nitrates/nitrites – High confidence that nitrate/nitrite will not impact groundwater due to destruction during process and added nitrate/nitrite had limited impact in the 2017 IDF PA from secondary wastes.

1.2.2.5. Ammonia/ammonium ion – Moderate confidence overall. Liquid secondary waste streams will contain significant ammonium that can be converted to ammonia in alkaline condition. Use of an ammonia tolerant grout can limit ammonia release in processes but long-term stability unknown. From the waste form, ammonia can both evaporate as vapor and leach to soil. Mitigated during the compliance period by low amount of water infiltration.

1.2.2.6. RCRA metals – High confidence that RCRA metals (except mercury) will be effectively immobilized in a primary waste form with low leach rates. Mercury is partitioned entirely to secondary waste streams.

  1.2.2.6.1. Mercury low confidence in overall fate – Mercury to partition to GAC where it will be stabilized/macroencapsulated as solid secondary waste. High confidence in ability to pass TCLP using slag in grout formulation with a high confidence in ability to sequester due to mercury sulfide formation. High confidence in limited subsurface transport, limited knowledge on speciation changes in subsurface. Expect to be absorbed primarily in sulfur-impregnated carbon bed; but will be widely distributed in the offgas system and some to LERF/ETF; mercury leaching from carbon bed has been tested but not elsewhere in the system.

  1.2.2.6.2. Chromium – High confidence in expected retention in glass waste form, refractory, and bubblers with low leach rates from glass dictated by stability of the glass.

  1.2.2.6.3. Other RCRA metals – High confidence that other RCRA metals are expected to be in glass waste form and expected to leach at rate dictated by the durability of the primary glass waste form.

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[2] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 *Waste Classification* that is used to classify wastes for near surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.3. Confidence in total volume of primary and secondary waste forms produced

Overall moderate confidence. High confidence in volume reduction of primary waste form. Medium confidence in amount of secondary waste generated – if total operating efficiency (TOE) is lower than projected, it would lead to higher secondary waste volume per liter of feed, which would lead to larger amounts disposed of in IDF.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.

[MOE is time to start and processing duration risk of tank leaks for both double-shell tanks (DST) and single-shell tanks (SST) is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage. (See tank leak discussion in Volume I, Section 1.3.2 for more detail). Startup in ~25 years, 3-year ramp up to full processing rate, low flexibility in processing rate, moderate throughput/TOE, complex and unique components, high maintenance needs, and large secondary waste handling needs increases risk of delays and therefore increases risk of additional leaks. Startup of this process in ~25 years has high risk of additional tank leaks because retrievals would be delayed vs. the schedule to support high-level waste (HLW), increasing time available for corrosion-induced leaks due to ongoing tank degradation.

Continuity of operations after startup – loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Because this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative consumes the entire initial benchmark supplemental LAW treatment budget, providing no opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is no potential for reducing risk of leaks.

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Multiple hazards. The high temperature process results in volatilization of selected radionuclides, increasing the risk for worker exposure. In addition, the buildup of radionuclides (^{99}Tc, ^{137}Cs, ^{129}I, others) in the recycle flywheel between the melter, offgas, and evaporator systems increases the exposure risk. The size and scope of the operations increase the number of workers exposed during normal operations and the extensive use of consumables (e.g., bubblers, melters, HEPA filters, GAC) require frequent exposure of these workers to hands-on maintenance activities with potential direct exposure to the radioactive material. Construction would be near operating radioactive facilities and ground contamination (i.e., contamination risk due to high vapor concentration due to flywheel, secondary waste handling, and extensive maintenance).

2.2.1.2. Chemical exposure – Multiple hazards. Similar to radiation exposure, the high temperature process results in volatilization of selected chemical species of concern and the generation of toxic offgas, increasing the risk for worker exposure.

In addition, the buildup of species (e.g., mercury) in the recycle flywheel increases the exposure risk. The size and scope of the operations increase the number of workers exposed during normal operations and the extensive use of consumables (e.g., bubblers, melters, HEPA filters, GAC) require frequent exposure of these workers to hands-on maintenance activities with unavoidable direct exposure to the chemical species. Furthermore, the use of hazardous chemicals (e.g., NaOH, anhydrous ammonia) in the process add to the hazards faced by workers. (38 high hazard consequences [RPP-RPT-63328].)

2.2.1.3. Particulate exposure – Few hazards that are not easily mitigated. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates. Mitigated by common commercial practices.

2.2.1.4. Physical injury – Moderate hazards. The large number of maintenance and other activities required for the vitrification process increase the exposure of hands-on workers to industrial hazards. 38 high hazards conditions were noted by Washington River Protection Solutions, LLC (WRPS) for vitrification of LAW (due to large number of maintenance activities) (RPP-RPT-63328).

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments of rad/hazardous shipments to high number of rad/hazardous shipments.)] – Low risk. The vitrification alternative generates the lowest waste volume amongst alternatives, and it is expected that all waste is disposed of in the IDF leading to the lowest possible transportation risk. Transport of hazardous chemicals (NaOH, anhydrous ammonia) to the site represents an exposure risk due to accidents.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] (High discharge volumes; new ETF believed necessary.) – Water is not incorporated in the primary waste form and large volumes of water are added during the treatment process. The liquid effluents from the vitrification process require additional treatment prior to release, using the existing LERF/ETF or a new, similar facility. A large fraction of the ^{129}I from the waste feed is expected to be in the liquid secondary waste and could result in an additional waste stream if the ^{129}I must be removed prior to sending the effluent to LERF/ETF. Approximately 2-3 gallons of treated wastewater will be sent to SALDS for each gallon of supplemental LAW feed. Tritium is all released to the environment [SALDS] immediately.

2.3.2. Atmospheric discharges

[MOE: Fraction of radionuclides and contaminants of concern (CoC) converted to vapor in offgas system.] – Expect 34 MT NH_3 and 4 MT “other” per 1 Mgal feed; 0.006 mrem ^{14}C discharge (RPP-RPT-63328); potential for ^{129}I.

2.3.3. Transfer/process tank (on-site) spills

[Unplanned discharges MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category.)] (Low – only risk is transfers to LERF or Effluent Management Facility [EMF].) – The large number of unit operations and high temperature operations, the corrosive nature of the recycle stream generated, and the use of corrosive chemicals increase the chances for on-site spills during treatment compared to other options (but all transfer lines have secondary containment).

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk. No shipments of liquid and no off-site immobilized waste. Off-site transportation risks include delivery of chemicals, including liquids such as sodium hydroxide and anhydrous ammonia, diesel fuel, and other industrial chemicals and glass-forming chemicals (GFC)/minerals.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment); low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – Very high volumes. Millions of gallons of liquid secondary waste are generated annually, leading to the requirement for additional treatment capacity at the LERF/ETF. In addition, the short operating life of components of the vitrification process (e.g., melters, bubblers) and the large number of consumables (e.g., HEPA filters, GAC media) lead to large volumes of solid secondary waste. The waste streams will likely contain significant portions of the ^{129}I, all the mercury, and some of each of the other CoCs in the waste feed. Spent melters are placed in containers and disposed of in IDF. Melters have an estimated operational lifetime of five years.

2.3.6. Greenhouse gas emissions (see Section 2.3.2 above) – At a minimum, treatment of 1.0E6 gallons of waste consumes 1,500,000 gallons (4,800 MT) of diesel fuel (~15,000 MT as CO_2), 168 MT sugar, 283 MT soda ash (sodium carbonate), 295 MT lithium carbonate (total of ~550 MT as CO_2), 74 GWh of electricity, and requires approximately 570 deliveries of fuel oil, glass formers, and other process chemicals (based on information from RPP-RPT-63328, and DOE/RL-2022-33, *Hanford Energy Emissions 2022-2037 – Reducing the Gap to Net Zero*[3]).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – The existing WTP LAW Vitrification Facility required approximately 20 years to complete. A supplemental LAW vitrification facility is expected to be at least twice as large as the WTP LAW Vitrification Facility and should be expected to take at least as long to construct. However, some efficiencies in design and construction could occur since the design is expected to be similar to the existing WTP LAW Vitrification Facility. In the benchmark funding scenario, the cost of the vitrification facility would extend the required schedule and would likely preclude completion of the facility in the time required. Hot start-up (CD-4) in ~2050 (see Volume II, Appendix F).

2.4.2. Duration to full capacity (additional years) – The facility would need to ramp up to full production in a short period of time (6 months) to support HLW processing. However, startup of similar facilities indicate that is more probable that a supplemental LAW facility would require 3 years to ramp up to full operations.

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[3] Fuel oil and deliveries amount adjusted for annual consumption in DOE/RL-2022-33 vs. 1M gal of waste in 154 days per RPP-RPT-63328.

2.4.3. Duration of operations (additional years) – The facility would operate until the end of the entire HLW campaign. HLW campaign will begin later because the supplemental LAW treatment starts later. Additional delay to supplemental LAW treatment startup extends duration that existing equipment and first LAW melters must operate, exacerbating maintenance needs and requiring replacement of equipment and facilities that exceed their design life.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues – Moderate risk that technical issues could delay startup. Expect first LAW to inform supplemental LAW melter design and operation, along with lessons learned from the Defense Waste Processing Facility and West Valley melters and pilot testing at Catholic University of America. Uncertainty exists in radionuclide partitioning and behavior across all waste compositions, production of LDR organics, along with overall integrated system complexity and additional facilities needed (e.g., ETF). (Delays due to technical uncertainties contribute to increased cost risk and therefore the potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – Very high risk of delay. Complex system with high maintenance requirements, multiple melters with partially shared systems, long operating duration, high temperatures, extensive balance of facilities, can contribute to potential extension of supplemental LAW and HLW processing duration.

3. Likelihood of successful mission completion

(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Tech failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste, i.e., failure mode likelihood and result – this should be customized for each alternative with each unique failure mode and consequence.) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] The vitrification alternative will use the same flowsheet and approach as the existing WTP LAW Vitrification Facility. Portions of the process have been extensively tested using pilot-scale systems, but selected unit operations have very limited or no testing (e.g., the GAC and caustic scrubber). Uncertainty remains in the partitioning of selected species, but the baseline process is considered robust and able to immobilize the waste sodium in a glass waste form.

3.1.1.1.1. Corrosion of offgas system causing frequent extensive repairs/replacement – Very low risk of failing to complete, despite high volatility and recycling of offgas condensate leads to rapid corrosion of offgas system components (where mercury has been absent from testing but not believed to cause dramatic impact; pilot-scale system could have differences). Consequence: Frequent shutdown and component replacement.

Mitigated by operation of the WTP LAW Vitrification Facility that will help guide material of construction for supplemental LAW treatment.

3.1.1.1.2. Fire in offgas system – Low risk of failure to complete, but there is potential for fire in carbon bed; supplemental LAW could have different offgas components (organics, NO_x) (where mercury has been absent from testing but not believed to be impactful; pilot-scale system could have differences). Monitoring of gases and temperature in GAC mitigates risk. Consequence: Extended duration shutdown; system redesign/rebuild. Extended delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide process for supplemental LAW treatment.

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or mercury or NH_3 (above permit) to atmosphere – Risk is unexpected partitioning of species under melter and offgas system operating conditions but would be mitigated if release occurs, so very low risk of failure to complete (pilot-scale system could have differences). Consequence: extended duration shutdown, system redesign/rebuild. Extended delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide design and operations for supplemental LAW treatment.

3.1.1.1.4. Ability to control WESP as it ages – Very low risk potential to make collection of technetium ineffective; risk is unexpected partitioning of species under melter and offgas system operating conditions (where pilot-scale system could have differences). Consequence: extended duration shutdown, system redesign/rebuild. Delays. Mitigated by operation of the WTP LAW Vitrification Facility that would help guide design and operations for supplemental LAW treatment; ability to wash technetium from HEPA filters or dispose of offsite.

3.1.1.1.5. Overall uncertainty of I partitioning – Iodine partitioning was tested, so low uncertainty remains, but problematic amounts could distribute to caustic scrubber solution bound for ETF. Consequence: excess partitioning to caustic scrubber requiring mitigation instead of sending to LERF/ETF. Mitigated by data from LAW melter operation.

3.1.1.2. Process complexity (flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Very high process complexity. Vitrification of the supplemental LAW feed requires a large number of integrated unit operations and incorporation of a significant and variable recycle stream into the feed process. The high temperature processing generates an offgas that both requires extensive treatment prior to release and worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement. The large recycle and extensive treatment system represent an interdependent and complex system where not all interactions are well understood.

Note that if designed the same as the LAW melter system, a single unit operation failure in the system will shut down the melter (or multiple melters for the secondary offgas system or GFC preparation system). In addition, the short cycle times of many of the feed and condensate handling processes require rapid turnaround of sample analyses, expedited batching of GFC batches, and complicates handling of the large number of receipts needed to keep the GFC silos and other process chemical feed tanks filled unless the feed tanks for supplemental LAW treatment are sized using a different basis than the current WTP LAW Vitrification Facility (very high interconnectedness). Consequence: Challenging to run system, delayed processing, additional costs, missed milestones. Mitigated by LAW Vitrification Facility operation providing input to operation and design but very high operating cost per day.

3.1.1.2.1. Unit Operations (33 systems listed below)

- Feed preparation tasks
  - Receipt of feed and recycle
  - Melter feed preparation
  - GFC batching
  - GFC blending and transfer
  - Melter feed system
- Melter
  - Feed compositional controls (high complexity)
  - Bubbler system (moderate complexity)
  - Cooling water system for refractory panels
  - Cooling for electrodes
  - Air lifts for pouring
  - Power supplies and electrode (moderate complexity)
- Primary offgas
  - Film cooler
  - Submerged bed scrubber
  - Wet electrostatic precipitator or steam atomized scrubber (high complexity)
  - Condensate collection
- Secondary offgas
  - Heater
  - HEPA
  - Activated carbon bed (moderate complexity)
  - Heat exchanger
  - Heater
  - Thermal catalytic oxidizer
  - Selective catalytic reduction unit (moderate complexity)
  - Caustic scrubber (moderate complexity)
- Effluent Management
  - Melter offgas condensate receipt and pH adjustment
  - Evaporation (moderate complexity)
  - Evaporator condensate collection and transfer to LERF/ETF

  - Evaporator concentrate collection and return to feed preparation process
- Container handling line
  - Pour cave
  - Fill height verification and inert fill station
  - Lidding station
  - Container swabbing and decon station (moderate complexity)
  - Container load out station.

3.1.1.2.2. Accuracy of controls needed

- Sampling/measurements needed to control process – Very high complexity. Batch qualification is expected to give composition for GFCs, but the internal recycle of concentrated melter condensate must be factored into the process. Sampling of the batch feed on a campaign basis, samples of each batch of recycle concentrate, and confirmation of the melter feed blend is currently performed for WTP LAW Vitrification Facility operations. If the process is closely coupled with HLW operations, additional sampling will be needed to account for the feed variations from the HLW effluents. In addition, sampling of the primary offgas condensate prior to evaporation and of the EMF evaporator condensate is expected during campaign transitions and if upset conditions occur.

  Control of the melter feed process is more art than science as the amount of cold cap coverage must be inferred from secondary indications and the response of the system to changes can take several hours. The secondary indications included melter pool and plenum temperatures. Cold cap coverage is controlled using melter feed rates and melter bubbling rates.

  These parameters also impact the reactions that occur in the melter plenum space such as reactions of nitrate to nitrogen, nitrous and nitric oxides, and ammonia, and the amount of feed organic destruction and production of organics from sugar. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

- Modeling needed to control process – Very high complexity. The vitrification process is driven by compositional requirements to efficiently process in the plant and produce an acceptable glass with predictable properties. The glass composition models predict the glass viscosity, liquidus temperature, product consistency test (PCT) and vapor hydration test (VHT) response, solubility of key components (e.g., sulfur, chromium), and electrical conductivity. The model is also used to predict glass composition for reporting purposes. Uncertainty in sample analysis accuracy and models. Consequence: See items below. Mitigated by experience with LAW melter operation.
  - Failure modes for improper operation
    - Glass viscosity

    - Improper viscosity (low or high) can cause the pour stream to drip, leading to strands of solidified glass between the pour spout and container. The pour stream can be diverted by these strands and could miss the container. Pour cell cameras are installed to monitor the pouring operation.
- Improper composition
    - High sulfur – If excessive sulfate is fed to the melter (or insufficient sugar) a gall layer can form on the surface of the melter that could lead to early failure of the bubblers and/or melter.
    - High chromium – Could lead to formation of crystals in melter.
- Liquidus temperature
    - Crystal formation could be mild or severe depending on magnitude of error. A gross error leading to large amounts of crystal formation is not considered likely. A small amount of crystals from a minor error could likely be handled by the vitrification system, but it is possible for crystal formation to negatively impact the melt composition leading to changes in viscosity, conductivity, etc.
- Electrical Conductivity
    - As with liquidus temperature, large errors that would lead to major processing issues are not expected. Improper electrical conductivity would lead to issues with maintaining the melter at temperature.
- PCT and VHT
    - PCT and VHT responses are modeled with no feedback mechanism in place during processing if the models are inaccurate at predicting glass performance. It will not be known that the glass did not meet durability limits unless future testing indicates issues with the specific composition poured or excessive leach rates are noted from the disposal site. The likelihood of glass composition issues causing excessive leaching from the IDF is considered low.
- Container composition
    - The composition of the glass in the container uses a simple model for single-pass glass retention for each species in the feed to predict the composition of the poured glass. The model currently does not account for cold cap coverage, idling, or other processing conditions. Thus, the composition of semi-volatiles in the reported glass compositions is likely to have a high amount of uncertainty.

3.1.1.2.3. Commercially available/similar (of a type) to available/bespoke systems – High number of custom components. Portions of a supplemental LAW vitrification facility could use commercially available equipment (e.g., exhaust fans, mixers, pumps), most components are of similar type systems modified for the supplemental LAW treatment facility and some systems are complete bespoke (e.g., melters, film coolers). Consequence: need to redesign/rebuild, causing mission delays. Mitigation is to get business to make replacement; build in on-site shop; purchase extras.

3.1.1.2.4. Overall flowsheet integration complexity – The flowsheet for a vitrification facility for supplemental LAW is extremely complex. The recycle of offgas condensate to the front end creates variability in the feed, a large number of GFCs must be accurately added to achieve high waste loadings using complex models to determine the required amounts for each batch, the feed to the melter must be distributed across three zones, the cold cap coverage must be inferred from secondary indicators, and the offgas system consists of 12 separate unit operations. The condensate from the primary offgas system must be evaporated and recycled. Two separate liquid effluent streams are generated, along with several solid waste streams. Life expectancy of the melter bubblers is expected to be ~6 months, requiring frequent maintenance on the melters to be balanced with the operating schedule. Operating experience from WTP LAW Vitrification Facility will help with the supplemental LAW treatment facility design and operation. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed) – Vitrification requires extensive utilities, including large demands for diesel fuel, cooling water, electricity, steam, and compressed air, and process chemicals such as anhydrous ammonia, sodium hydroxide, sugar, and 12 GFCs. Sample requirements necessitate an integrated analytical facility operating on a 24/7 schedule. Cross-site supernatant liquid transfer line is needed to support this alternative. Secondary waste generation and limited lag storage require treatment facilities for these streams to be available. Operating experience from WTP LAW Vitrification Facility will help with the supplemental LAW treatment facility design and operation. Consequence: Delayed processing, complex interrelated systems, melter idling causing variability in recycle composition. Mitigated by experience with LAW melter operation.

3.1.1.4. Required demolition/removal/modification
It is expected that siting will not require demolition or removal of existing facilities. No consequences.

3.1.1.5. Technology Maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – The vitrification alternative will use the same flowsheet and approach as the existing WTP LAW Vitrification Facility. Portions of the process have been extensively tested using pilot-scale systems. Uncertainty remains in the partitioning of selected species, but the baseline process is considered robust to be able to put the waste sodium into a glass waste form. WTP LAW processing of direct-feed low-activity waste (DFLAW) feed should reduce uncertainty in the partitioning of these species while the supplemental LAW treatment facility is built. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – WTP LAW processing of DFLAW feed should reduce technical uncertainty while the supplemental LAW treatment facility is built. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[High heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – The ability to adjust waste loading and GFC recipe will allow a supplemental LAW vitrification facility to handle a wide range of feeds. Predicted waste soda loading for LAW range from 3-4% up to 25% with most batches over 20%. Non-pertechnetate is not an issue for the vitrification process since any non-pertechnetate not retained by the glass will react to form pertechnetate in the melter offgas system. Consequence: Delayed processing. Mitigated by experience with LAW melter operation.

3.1.4. Ability to incorporate future advances
[MOE: Easily incorporated to impossible.] – The high capital cost and unique operations makes incorporation of future advances challenging. Consequence: high cost of changes.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW budget.] – The funding needs for a supplemental LAW vitrification facility will likely exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – The peak funding needs for a supplemental LAW vitrification facility will likely greatly exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – Vitrification facilities have limited ability to operate at lower rates than needed to maintain a cold-cap on the melter as operating with a small cold cap results in excessive losses of semi-volatiles to the offgas. Idling the melter at temperature to allow enough feed to accumulate to allow operation for a period of time with a full cold cap also results in high semi-volatile losses. A cold shut down requires the melter to be replaced. Given that multiple melters are required, it may be feasible to allow a portion of the melters to remain in extended idle during periods of reduced feed, but this option still uses significant resources and melter life is not extended by idling. The "SLAW feed vectors" have considerable variability in the amount to be treated each month. Sufficient lag storage to provide a constant feed to the supplemental LAW treatment facility is not feasible.

3.2.4. Expected work remaining at failure point

[MOE: failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; text to funding shortfall/timing; describe when it fails; MOE is consequence only.) – A supplemental LAW vitrification facility failure is assumed to be caused by lack of funding during construction. Consequence: Alternate technology/solution must be developed. Delayed mission, delayed start of supplemental LAW processing. It is unlikely that sufficient funds will be available to complete a vitrification facility by the project need date.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility does not complete and never starts up. Start of the supplemental LAW treatment mission is delayed. Worst case is to commit to vitrification option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. It is unlikely that sufficient funds will be available to complete a vitrification facility by the project need date.

3.3. ***Likelihood and consequences of failing to complete due to*** **unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider)] – The refractory used for the melters and other components have a single U.S. vendor. One system, the carbon dioxide decontamination system, has already been removed as a result of the vendor going out of business (along with previously unresolved issues with asphyxiation hazards).

Analytical services for WTP are provided by an on-site laboratory; this laboratory may not be able to handle the sample load from supplemental LAW vitrification facility with multiple melters, depending on configuration and sample requirements. Consequence is switching to an available material/equipment, expand capability, etc.; potentially causing additional cost and delays. While some delays may occur, a supplemental LAW vitrification facility is sufficiently large that it is not likely that a provider would be unwilling to provide materials or specially engineered parts.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above (all costs are discounted at 3% rate).

Total: $12,700 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$7,608 M (includes commissioning costs)

Note – Evaporation assumed provided by mission as part of HLW feed preparation facility.

4.2. Operations costs

$5,092 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

C.2.2 Selection Criteria Assessment for Alternative FBSR 1A

Alternative FBSR 1A: Fluidized Bed Steam Reforming On-site (A) Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – all retained – amount increased by treatment.]

1.1.1.1. Nitrates/nitrites – Low residual toxicity. Nitrate/nitrite are destroyed by fluidized bed steam reforming (FBSR) and in the offgas system, and are essentially nondetectable in the primary waste form, but the offgas still contains some NO_x gas species. Nitrates were destroyed to detection limit levels (0.002 wt%) in the mineralized product, and overall offgas NO_x destruction was measured at between 91-94%, exceeding the goal for the Hanford LAW and WTP secondary waste simulants tests. (RT-21-002, *Report for Treating Hanford LAW and WTP SW Simulants: Pilot Plant Mineralizing Flowsheet*). Trace amounts of nitrate in the primary waste form would be insignificant in the disposal environment.

1.1.1.2. RCRA metals – High residual toxicity. RCRA metals are contained in the primary waste form except for mercury. All mercury is presumed to evolve to the offgas. All primary offgas components will have mercury contamination and secondary offgas components will have mercury contamination up to the GAC. Mercury captured on the sulfur-impregnated GAC would be micro-encapsulated in grout. No destruction.

1.1.1.3. LDR organics – Low residual toxicity. Most organics are destroyed by the FBSR and secondary offgas process. Some organics may be generated by incomplete combustion of coal but would be destroyed in the thermal oxidizer (TO). Organics in waste largely destroyed to non-detectable levels in the primary waste form, remaining organics destroyed in offgas system to within regulatory limits. Leftover coal in primary waste form, but not believed to be an issue.

1.1.1.4. Ammonia – Very low residual toxicity. The FBSR process should destroy whatever ammonia is in the LAW and does not introduce ammonia into the system. Ammonia and related compounds are likely produced in the denitration and mineralizing reformer (DMR) but are expected to be destroyed in the TO. No ammonia for long term impact.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Selected findings from the ASTM C1285, *Standard Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses and Multiphase Glass Ceramics: The Product Consistency Test (PCT)*, short-term and long-term durability testing, single pass flow-through (SPFT) testing, and pressure unsaturated flow-through (PUF) testing of the FBSR granular waste form produced from bench-scale, pilot-scale and engineering-scale testing indicate that (1) ASTM C1285 (PCT) releases would be expected to be near or more likely well below 2 g/m^2 (target), which means short-term, static release is comparable to processable WTP glasses,[1] (2) SPFT test data for silicon from the Savannah River National Laboratory (SRNL) bench-scale reformer (BSR) with modified radioactive tank waste product are two orders of magnitude lower than the data for LAWA44 glass, and (3) PUF test data indicates that rhenium release (analog for technetium) from a multiphase FBSR sodium aluminosilicate granular product is an order of magnitude lower than ^{99}Tc release from LAW glass (LAW AN102) (SRNL-STI-2011-00387, *Fluidized Bed Steam Reformed Mineral Waste Form Performance Testing to Support Hanford Supplemental Low Activity Waste Immobilization Technology Selection*; SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*). Thus, the normalized dissolution rates of the FBSR granular product are within the ranges of normalized dissolution rates for borosilicate glasses with compositions within the processable compositions of Hanford's WTP (PNNL-14805, *Waste Form Release Data Package for the 2005 Integrated Disposal Facility Performance Assessment*; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063, *Chemical Composition and PCT Data for the Initial Set of Hanford Enhanced Waste Loading Glasses*; PNNL-28838, *Enhanced Hanford Low-Activity Waste Glass Property Data Development: Phase 2*).

1.1.2.1.1. Iodine (Iodine mobility to groundwater is limited during the first 1,000 years compliance period due to facility performance) – Iodine is expected to partition predominately to the granular product (SRNL-STI-2011-00387). Release rates for iodine are expected to be near or more likely well below the 2 g/m^2 target (ASTM C1285 [PCT]) for the FBSR granular product and monoliths (SRNL-STI-2011-00387).[1]

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[1] Accounting for the surface roughness of the mineral granules indicates that the FBSR product leach rate would likely be two orders of magnitude lower than the 2 g/m^2 target and, when the surface roughness of the mineral granules is ignored, that the FBSR product has an equivalent leach rate to "vitreous waste forms" (SRNL-STI-2011-00387).

However, PCT alone on a pristine waste form is not necessarily indicative of long-term disposal (i.e., IDF) performance (e.g., without additional information on alteration phases, thermodynamic and rate law parameters, structural incorporation).

The previous comparative performance estimates based on PCT, SPFT, and PUF results for a single-vendor steam-reforming material (RPP-17675, *Risk Assessment Supporting the Decision on the Initial Selection of Supplemental ILAW Technologies*) that suggested "*[g]iven the uncertainties, the groundwater impacts [and thus the normalized dissolution rates] of SR [steam reforming] are comparable to those of WTP glass*" are uncertain (including structural incorporation of ^{99}Tc and ^{129}I inferred from leaching results and how thermodynamic and rate model parameters were estimated without uncertainty quantification) and can be considered optimistic estimates.[2]

To date, only rhenium has been shown to exist in sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015; Pierce et al., 2014). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. No observation of iodine incorporation into the sodalite cage from the FBSR process has been made to date. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). Furthermore, there is direct evidence of iodine incorporation into sodalite cages in studies focused on vapor-phase capture of iodine using sodalite materials (Maddrell et al., 2014; Sava et al., 2011), which suggests that iodine may also be structurally incorporated in the steam reforming granular product sodalite phase. Some iodine may be sorbed onto the GAC, quantity is uncertain.

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[2] In RPP-17675, all ^{99}Tc was assumed to be in the nosean phase and other contaminants (including ^{129}I) were assumed to be released in proportion to the rate at which ^{99}Tc was released from the nosean phase. The sodalite phase (which is isostructural with nosean and considered the host phase for ^{99}Tc and ^{129}I in more recent steam reforming studies (SRNL-STI-2011-00387) was not considered in the Preliminary Risk Assessment. These inferences are further complicated by the possible solid solution with sodalite and nosean as end members that may be present in the granular product (SRNL-STI-2011-00387). Additional testing suggests that dilute, steady-state dissolution rates are consistent with earlier data; however, there remain questions to be resolved, including (1) the applicability of Transition State Theory to the multimineral phase granular steam reforming product and corresponding model uncertainty; (2) the estimation and uncertainty quantification of thermodynamic and rate model parameters (e.g., activation energy, log K) other than the intrinsic rate needed for long-term performance prediction, especially for any solid solutions formed; (3) the locations of ^{99}Tc and ^{129}I based on solid phase measurements to confirm the hypotheses (i.e., structural incorporation in the sodalite cage) inferred from leaching results; (4) the rate of re-oxidation of the granular product during disposal (allowing release of ^{99}Tc not in the sodalite cage); etc.

1.1.2.1.2. Technetium (Non-pertechnetate was evaluated in Section 1.2.2.2; technetium mobility to groundwater is limited during the first 1,000 years [compliance period] due to facility performance) – Most (~99%) ^{99}Tc will be retained in the primary granular waste form, which exhibits very low leach rates either from structural incorporation in sodalite or the reduced nature of the granular product (SRNL-STI-2011-00387).[3] The release rates would likely be within those for borosilicate glasses with compositions within the processable compositions of Hanford's WTP (PNNL-14805; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063; PNNL-28838), but dependent on partitioning, structural incorporation,[2] and reoxidation of the waste form during disposal. To date, only rhenium has been shown to exist in the sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium, providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). A small fraction will be captured on the HEPA filters, which are crushed and macroencapsulated in grout. Leach rates from the spent HEPA filters are evaluated in the current PA, but the inventory to be disposed of is TBD. Expect about same amount on HEPA filters as in vitrification. Better single-pass retention of technetium in primary waste form vs. vitrification, leading to less technetium in offgas/HEPA filters.

1.1.2.1.3. Selenium-79 (^{79}Se) – Assumed to partition like sulfur, with most ending up in the primary waste form with very low leach rates. Like ^{99}Tc, a small portion could be captured on the spent HEPA filters that are macroencapsulated and disposed of in IDF. Expect about same amount on HEPA filters as in vitrification. Minimal impact due to limited quantity; 114 Ci total in the Hanford tank farms (per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*, see Volume II, Section E.3.1.3). Assuming high mobility from waste form release to subsurface is many orders of magnitude below conservative DWS.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

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[3] X-ray absorption spectroscopy (XAS) data on technetium indicates that the +7 oxidation state in the sodalite cage is between 65-79% in the reduction-oxidation (REDOX) range of the FBSR operation with remainder as +4 in TcO_2 oxide and/or $Tc_2S(S_3)_2$. During durability testing, including long-term testing, there was no change in durability with sample REDOX, indicating that the +7 fraction of the technetium is insoluble in the sodalite cage, while the +4 fraction of the technetium is insoluble in the oxide and/or sulfide form (SRNL-STI-2011-00387).

1.1.2.2. Nitrates/nitrites [MOE: Estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – N/A, destroyed in DMR.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives.] – Ammonia in tank waste is destroyed in the FBSR process. DMR may produce ammonia but will be destroyed in the TO and not present in solid waste form.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Leach rates of RCRA metals from the granular waste are expected to be very low either from the nature of the granular product or low inventory in the LAW feed (SRNL-STI-2011-00387).[4] Only exceedances of TCLP Universal Treatment Standards (UTS) limits to date were for elements intentionally spiked above realistic limits.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Mercury will not be retained in granular product and will end up in the activated carbon waste form, which is assumed to be encapsulated in grout. Expect geopolymer waste form and encapsulated GAC grout to pass TCLP.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form.] – Chromium will be captured in the primary waste form with very low TCLP leach rates, although additional iron oxide catalyst (IOC) may be required where this material is also used as a denitration aid in the FBSR process (SRNL-STI-2011-00387). Like technetium, a small fraction could be partitioned to the spent HEPA filters that are macroencapsulated in grout and disposed of in IDF. Expect geopolymer waste form to also pass TCLP.

1.1.2.4.3. Other [No MOE needed.] – Projected concentration of other RCRA metals is not known but expected to pass TCLP (SRNL-STI-2011-00387). Some TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (where inventory is not recorded in the Best Basis Inventory [BBI] [2018]) because only small quantities of these chemicals are present in the waste and analytical data are limited (HNF-SD-WM-TI-740, *Standard Inventories of Chemicals and Radionuclides in Hanford Site Tank Wastes*). Only ^{125}Sb is recorded in the BBI because only small quantities of the other antimony isotopes are likely present in the waste. The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes.

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[4] TCLP analyses for most of the RCRA metals were well below corresponding UTS (40 CFR 268.48, "Universal Treatment Standards," Non-wastewater) (SRNL-STI-2011-00387). However, some TCLP analyses for antimony, cadmium, and chromium exceeded UTS limits depending on the laboratory performing the analyses. After additional evaluation (including inventory considerations for cadmium and antimony), only the chromium analyses for the simulant exceeded the UTS; however, the granular product made using radioactive waste passed TCLP for all RCRA metals including chromium. The IOC, added to enhance denitration, could potentially be used as a co-reactant to sequester chromium as $FeCr_2O_4$ (SRNL-STI-2011-00387).

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – For 1 gallon of LAW feed: 1.0 gallon of primary waste form, 0.018 gallons of spent equipment, HEPA filters, spent carbon sorbent, etc., and no grouted solids (from ETF) (RPP-RPT-63580, *Calculating the Non-Monetary Impact of Operating a Fluidized Bed Steam Reforming Facility*, and SRNL-STI-2011-00387).

1.2. Long-term risks upon successful completion

Exogenous risks (earthquake, catastrophic flood, volcano, etc.) are assessed as indistinguishable across all technologies and disposal locations.
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics/destruction of organics – Presumably, all of the organics in the waste would be destroyed in the DMR or in the TO.

1.2.1.2. Nitrates/nitrites – High confidence that nitrate and nitrite will be nearly completely destroyed by the immobilization process. Testing done on varying conditions for over 20 years confirms thermodynamics of nitrated compounds – they thermally decompose at temperatures <400°C (i.e., well below 725-750°C in the DMR) and are destroyed to at or below detection limits in the mineralized product.

1.2.1.3. Ammonia/ammonium ion – None in primary waste form. No ammonia is added to the process. Ammonium compounds like ammonium nitrate and ammonium hydroxide are thermodynamically unstable or boil at temperatures above about 200°C, well below the 725-750°C temperature of the DMR. Ammonia and ammonium compounds are efficiently destroyed at temperatures typically between 850-950°C in the TO, which is designed to efficiently destroy thermally stable compounds such as hydrogen cyanide and benzene. But limited testing done on varying conditions and effectiveness of offgas system.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state. Expect essentially all mercury to sorb onto GAC based on pilot-scale testing but mercury retains its toxicity.

1.2.1.4.2. Chromium – High confidence in no change to toxicity in the Hanford environment. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity in the Hanford environment.

1.2.2. Confidence in immobilization with regard to groundwater

1.2.2.1. Iodine – High-moderate confidence that partitioning of iodine through process will proceed as expected (i.e., iodine will primarily end up in the granular product). Single-pass capture is high and minimal amounts in secondary waste form (GAC).

Low leachability expected in waste form where leaching tests (e.g., PCT, SPFT) suggest normalized dissolution rates of the FBSR granular product are within the ranges of normalized dissolution rates for borosilicate glass with compositions within the processable compositions of Hanford's WTP (PNNL-14805; Neeway et al., 2016; Vienna et al., 2018; Crum et al., 2021; SRNL-STI-2014-00063; PNNL-28838).[5] However, structural incorporation of iodine in the sodalite cage structure (as inferred from leaching results [SRNL-STI-2011-00387]) is uncertain – and thus is the long-term performance of the waste form for iodine during disposal – because no solid phase measurements (for iodine) have been performed to confirm the structural incorporation hypothesis. However, there is direct evidence of iodine incorporation into sodalite cages in studies focused on vapor-phase capture of iodine using sodalite materials (Maddrell et al., 2014; Sava et al., 2011), which suggests that iodine may also be structurally incorporated in the steam reforming granular product sodalite phase. Corrosion testing of FBSR granular products has also shown apparent congruent releases of iodine and technetium/rhenium, providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016) (see Section 1.1.2.1.1).

1.2.2.2. Technetium (including non-pertechnetates) – High confidence that nearly all technetium is captured in primary waste form; remainder (minimal) is captured in HEPA filters. Non-pertechnetate would be expected to decompose in DMR and behave similar to pertechnetate from waste. Low leachability in waste form. Structural incorporation of technetium in the sodalite cage structure (as inferred from leaching results [SRNL-STI-2011-00387]) is uncertain – and thus also is the long-term performance of the waste form for technetium – because no solid phase measurements (for technetium) have been performed. To date, only rhenium has been shown to exist in the sodalite cage resulting from steam reforming of Hanford LAW (Dickson et al., 2014; Mattigod et al., 2006; Dickson et al., 2015; Pierce et al., 2014). Rhenium can be a suitable surrogate for technetium, and it was inferred that technetium could also be incorporated into the sodalite cage of the FBSR product. Corrosion testing of FBSR granular products has shown apparent congruent releases of iodine and technetium/rhenium providing circumstantial evidence that the elements are likely present in the same mineral phase (Neeway et al., 2016). Furthermore, the fraction of technetium that would not be structurally incorporated in the sodalite cage would be insoluble in the oxide and/or sulfide form (SRNL-STI-2011-00387). Thus, the release of technetium not structurally incorporated in sodalite would be expected to be low as long as the waste form remains reduced (i.e., is not reoxidized) (see Section 1.1.2.1.2).

1.2.2.3. ^{79}Se – Medium confidence that selenium will behave similarly to sulfur and be incorporated into primary waste form with low leach rates. Spiked non-radioactive selenium found to pass RCRA limits by TCLP testing, indicating retention in the waste form (SRNL-STI-2011-00387). Chemistry is expected to mimic sulfur. High confidence in small inventory, 144 Ci total (per RPP-ENV-58562).

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[5] Release rates are expected to be near or more likely well below the 2 g/m^2 target (ASTM C1285 [PCT]) for the FBSR granular product and monoliths (SRNL-STI-2011-00387) (see Section 1.1.2.1.1).

1.2.2.4. Nitrates/nitrites – High confidence that nitrate/nitrite will not impact groundwater due to destruction during process.

1.2.2.5. Ammonia/ammonium ion – Destroyed in TO. None in primary or secondary (GAC/HEPA filter) waste form.

1.2.2.6. RCRA metals – High confidence that most RCRA metals with sufficient inventory (except mercury) would be effectively immobilized in primary waste form with low TCLP leach rates. Mercury is partitioned entirely to secondary waste streams (GAC).

1.2.2.6.1. Mercury – Expect to be absorbed primarily in sulfur-impregnated carbon bed.

1.2.2.6.2. Chromium – Expect to be retained well in reduced granular primary waste form initially (that may also require additional IOC where this material is also used as a denitration aid in the FBSR process [SRNL-STI-2011-00387]), but no long-term testing on granular or monolith reoxidation has been performed.

1.2.2.6.3. Other RCRA metals – Other RCRA metals expected to be in granular primary waste form and not expected to be leachable via TCLP. TCLP leaching values for antimony and cadmium exceeded UTS limits; however, these values were shimmed in the feed (without regard for TCLP) to allow quantitative evaluation of mass balance/offgas results. High confidence in small inventory of cadmium (not recorded inventory in BBI because only small quantities of these chemicals are present in the waste and analytical data are limited [HNF-SD-WM-TI-740]). Only ^{125}Sb is recorded in the BBI because only small quantities of the other antimony isotopes are likely present in the waste. The total activity of ^{125}Sb (~615 Ci) as of 2018 translated to less than 0.5 gram in all Hanford tank wastes.

1.2.3. Confidence in total volume of primary and secondary waste forms produced – High-moderate confidence in volume reduction of primary waste form. Moderate confidence in amount of secondary waste generated.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk
[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage (see tank leak discussion in Volume I, Section 1.3.3 for more detail).] – High risk. Startup in ~15 years and 3-year ramp up to full processing rate, moderate flexibility in processing rate, undemonstrated throughput/TOE, complex and unique components, and potentially high maintenance needs contribute to high risk of delays and therefore increases risk of additional leaks.

Startup of this process in ~15 years has increased risk of additional tank leaks since retrievals would be delayed vs. the schedule to support HLW, increasing time available for corrosion-induced leaks due to ongoing tank degradation.

Continuity of operations after startup – Loss of specific DSTs is more impactful because of dependence on cross-site transfer line, specific feed piping, tank utilization, etc. Since this is a 200 East Area facility, it is more directly dependent on specific infrastructure, including DSTs, and would therefore be more impacted by failure of key staging and transfer tanks.

This alternative consumes the entire initial benchmark supplemental LAW treatment budget, providing no opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is no potential for reducing risk of leaks.

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Multiple hazards. The thermal process produces a granular and potentially dusty waste form, which contains radionuclides, increasing the risk for worker exposure if exposed to product dust. The size and scope of the operations increase the potential for worker exposure during normal operations. The presence of product dust in the process also increases the potential for worker exposure during maintenance. Engineered and administrative controls would be required to prevent worker exposure. Construction would be near operating radioactive facilities and ground contamination. Low volatility of rads but potential for radioactive dust (e.g., maintenance activities on offgas equipment or containers of granular product).

2.2.1.2. Chemical exposure – Multiple hazards. Various chemicals and feed materials are used in the FBSR process. Besides the supplemental LAW feed itself, the process feed streams include liquid nitrogen and oxygen, clay powder, coal, fuel oil, activated carbon, sodium hydroxide, and sodium silicate solution. Alumina is a required startup bed material. The process also produces gases (e.g., CO, NO, and NO_2) that are irritants or toxic above certain concentrations. While these gases are efficiently destroyed in the process, they can exist in any gas leaks in worker spaces and would result in toxic, irritating, or O_2-deficient conditions. Dusts produced in the process can also include irritants or toxic chemicals. The size and scope of the operations increase the potential for worker exposure to gaseous or particulate chemical hazards during normal operation or maintenance. These hazards require mitigation through engineered and administrative controls.

2.2.1.3. Particulate exposure – Multiple hazards. Dry process feed streams (clay, coal, activated carbon), alumina in the startup bed, and the dry product waste form (prior to forming a monolith) contain dusts that require engineered and administrative controls to prevent exposure to workers during operations and maintenance. Product is granular with potential dust from the process gas filters (PGF). Radioactive dust is contained within process equipment.

2.2.1.4. Physical injury – The FBSR process includes various potential physical hazards, including mechanical, high temperature, cryogenic O_2 and N_2, dust, and low-O_2 hazards, all of which require mitigation during construction, operation and maintenance. 34 high hazards conditions were noted by WRPS for FBSR treatment of LAW (RPP-RPT-63580). Engineered controls mitigate hazards; construction/design will mitigate.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad.] [MOE: Few trip/shipments of rad/hazardous shipments to high number of rad/hazardous shipments.] – Moderate risk. The FBSR alternative that disposes primary waste form in IDF generates the mid-range waste volume and all waste is expected to be disposed of in the IDF leading to low transportation risk. Granular waste volume is ~1× the liquid waste volume (bounding value of 1.2× used for calculations).

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Low risk. Water is not incorporated in the primary waste form. Water is added during the treatment process for steam production and temperature quenching. This water is all evaporated and exits the stack; no liquid secondary wastes are produced. For the geopolymer monolith primary waste form option, water is added that becomes part of the solid monolith waste form. (Tritium is all released to the environment [stack] immediately.) Minimal liquid to ETF (no process liquids, only other types of liquid wastes such as potential decon solutions).

2.3.2. Atmospheric discharges

[MOE: Fraction of radionuclides and CoCs converted to vapor in offgas system.] – Atmospheric radionuclide and CoC discharges will be within regulatory limits and are not expected to be a discriminator. Oxidation of organic CoCs, mercury capture, $^{129}I/^{99}Tc/^{14}C$ capture, destruction of nitrates and NO_x, gas scrubbing, and filtration for both vitrification and FBSR are expected to achieve regulatorily compliant results for air emissions.

2.3.3. Transfer/process tank (on-site) spills

[Unplanned discharges MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Minimal risk of on-site spills (all transfer lines have secondary containment). No liquids are discharged from facility.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – No shipments of liquid and no off-site immobilized waste in the case of disposal at IDF. Off-site transportation risks include delivery of chemicals, including liquids such as sodium hydroxide, coal, clay, alumina, liquid oxygen, liquid nitrogen, and other industrial chemicals.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment); low quantity of secondary waste to highest quantity of liquids, solids, and equipment.] – No secondary liquid wastes are generated. Moderate amount of debris (spent GAC and HEPA filters comparable to vitrification).

2.3.6. Greenhouse gas emissions (see Section 2.3.2 above) – At a minimum, treatment of 1 Mgal of waste consumes 984 MT of coal (~3,200 MT CO_2), 200,000 gal fuel oil or natural gas (~2,100 MT CO_2), 19 GWh of electricity, and requires nearly 416 deliveries of clay, coal, and process chemicals (based on data from RPP-RPT-63580).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) – ~15 years.

2.4.2. Duration to full capacity (additional years) – The Integrated Waste Treatment Unit (IWTU) at Idaho National Laboratory (INL) has required about 9 years (up to now) to start radioactive feed after initial plant startup, which was mainly due to lack of technology maturation and several issues identified during IWTU plant startup that were neither identified nor resolved during preconstruction pilot/demonstration testing. With those IWTU lessons learned, time was included in the FBSR schedule estimate in the National Defense Authorization Act for Fiscal Year 2017 (NDAA17) study to provide for more extensive pilot/demonstration testing prior to supplemental LAW FBSR plant construction.

Considering IWTU plant startup experience, prior mineralizing FBSR demonstrations, and future pilot-scale FBSR demonstrations that would be performed as part of a project if selected for Hanford supplemental LAW treatment, time to full capacity for FBSR should be similar to vitrification, ~3 years.

2.4.3. Duration of operations (additional years) – The facility would operate until the end of the entire HLW campaign. HLW campaign will extend duration because the supplemental LAW processing starts later. Additional delay to supplemental LAW treatment startup extends the duration that existing equipment and WTP LAW melters must operate, exacerbating maintenance needs and requiring replacement of equipment and facilities that exceed their design life.

2.4.4. Risk of additional mission delay

2.4.4.1. Delay due to technical/engineering issues – High risk. Technology has not been demonstrated at scale with waste representing expected variability and uncertainty to produce a mineralized waste form in an integrated system. Feed system and offgas system are complex. Limited knowledge of waste form performance (i.e., lack of solid phase characterization to support structural incorporation inferences from leaching data, lack of thermodynamic and rate law data, and uncertainty quantification needed to predict long-term performance). (Delays due to technical uncertainties contribute to increased cost risk and therefore potential for lengthening mission duration.)

2.4.4.2. Delay due to annual operating costs exceeding budget – High risk of delay. The FBSR is a complex system that includes many integrated subsystems that must all work together, or operations and maintenance costs may increase and exceed the annual budget.

3. Likelihood of successful mission
(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk – Risks of things that would stop the project before completion (i.e., failure – which could be because the solution is cost/schedule prohibitive).

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste [i.e., failure mode likelihood and result] – this should be customized for each alternative with each unique failure mode and consequence)
[MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The FBSR alternative will use a similar feed flowsheet and approach as the existing WTP LAW Vitrification Facility, although the Hanford LAW FBSR uses a TO instead of a carbon reduction reformer (CRR), which was used at IWTU and found to be troublesome during startup. Portions of the steam reforming process have been extensively tested using pilot-scale systems, but for other applications (e.g., IWTU producing a carbonate waste form) and waste streams (e.g., sodium bearing waste at INL). Uncertainty remains in the partitioning of selected species (between product and offgas) and structural incorporation of ^{99}Tc and ^{129}I in sodalite (as inferred from leaching results and other circumstantial lines of evidence, as described in Section 1.1.2.1.1 and 1.1.2.1.2), but the baseline process is considered of moderate maturity to be able to put the waste sodium into a granular waste form. IWTU lessons will be incorporated, but with different flowsheet and waste form; consequence is that technology would be challenging. If a failure was imminent, it would likely be identified during pilot-scale testing.

3.1.1.1.1. Corrosion of offgas system causing frequent extensive repairs/ replacement – (Limited testing. Moderate temperatures. Halides are captured in DMR and do not vaporize appreciably.) The commercial Erwin ResinSolutions Facility FBSR system (formerly Studsvik Processing Facility) in Erwin, Tennessee has operated since the 1990s, using similar mineralizing product chemistry (Mason et al., 1999). However, corrosion of the PGFs has been a cause of delay for the IWTU. This issue has been addressed with more pilot/demonstration testing and new filters (ceramic instead of Inconel, which corroded and caused plugging) have been installed in IWTU, and are now undergoing additional testing. Other potential corrosion issues include potential corrosion of offgas system piping, etc. during long-term operation, to be determined during IWTU operation. Corrosion is mitigated through process control and monitoring and avoided when operation is maintained within established operating limits. Consequence: Potential for frequent shutdown and component replacement, delaying the mission completion and high costs. Mitigated by operation of IWTU and pilot-scale testing that will help guide material of construction; moderately easy to shut down and restart).

3.1.1.1.2. Fire in offgas system – Low potential for fire in carbon bed or PGF. Potential for fire in the PGF is prevented by consumption of oxygen in the DMR, and subsequent minimal concentration of oxygen (close to 0 vol%) in the PGF. Supplemental LAW treatment is expected to contain organics and nitrates, which if not efficiently destroyed in the DMR and TO, could encourage oxidation of GAC particles and even fire in the carbon bed.

GAC is downstream of the oxidizer unit, which (together with the DMR) efficiently destroys organics. But some NO_x gas remains, along with about 3-5% O_2, in the oxidizer outlet gas. Potential for a fire in the carbon bed is mitigated through process control and monitoring of the gas composition and avoided when operation is maintained within established operating limits during normal FBSR operation. Consequence: CoC release to the environment, extended duration shutdown, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.3. Release of radioactive material (e.g., ^{129}I, ^{3}H) or other CoCs (e.g., mercury, NO_x) (above permit) to atmosphere (technetium/iodine radionuclides are not vaporized as much as with vitrification) – Risk is unexpected partitioning of species under DMR/PGF and offgas system processing due to operating conditions, or failure of offgas system components (TO, filters) to adequately destroy or capture CoCs. Consequence: Restore operating conditions back to within established operating limits (which are fast to accomplish) or, in the event of equipment failure, extended duration shut down, system redesign/rebuild, delaying mission and additional costs.

3.1.1.1.4. Ability to control offgas system as it ages (mitigate by replacing components on a schedule) – Low risk of unexpected partitioning of species under DMR/PGF and offgas system operating conditions. Consequence: Challenging operations, requiring periodic replacement of offgas system components (e.g., TO components, filters, or activated carbon) on planned or accelerated schedule without significant mission delay; or in the case of equipment failure, extended duration shut down, system redesign/rebuild.

3.1.1.1.5. Overall uncertainty of iodine partitioning – Low uncertainty. Liquid waste variability and rapid reactions could impact consistent partitioning (i.e., how much ends up in the offgas system) of the iodine. Consequence: Excess partitioning to offgas system requiring mitigation. Mitigated by adding/modifying components in the offgas system; determine need for required unit operations during pilot-scale testing.

3.1.1.1.6. Waste form leachability is higher than allowable – Radionuclide and hazardous metal retention based on the crystalline (sodalite/nosean) structure of the granular product and ability to consistently incorporate CoCs (especially iodine and technetium) in the sodalite cage structure and reducing chemistry in the granular product for technetium (SRNL-STI-2011-00387). Work has been done to demonstrate treatment effectiveness for selected Hanford LAW compositions (i.e., although not from designed studies) that do not adequately represent the variability and uncertainty in the Hanford LAW feeds that would likely need to be treated. This lack of representativeness translates to the consistency of the granular waste form produced from treating the high salt solution (with variabilities and uncertainties outside the tested ranges) in FBSR.

The hypothesis of structural incorporation of important radionuclides (^{129}I and ^{99}Tc) inferred from leaching results and supported by circumstantial lines of evidence (see Sections 1.1.2.1.1 and 1.1.2.1.2) and metal retention due to the reducing granular product require additional (designed) testing, but presumably these issues could be resolved prior to construction and startup. Consequence: High consequences that waste form leaches radionuclides or metals and cannot be disposed of without additional processing. (Mitigation method for off-specification material could include placing the product in a high integrity container (HIC), or off-site disposal in an acceptable commercial disposal site. Mitigation is assumed to not include sequestration by geopolymer.)

3.1.1.2. Process complexity [flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option]

[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Very high complexity due to interconnectedness. FBSR of the supplemental LAW feed requires a large number of integrated unit operations and incorporation of variable streams. The thermal process generates an offgas that both requires extensive treatment prior to release and worker protections to prevent exposure. The process contains many items that require routine hands-on maintenance or replacement; however, the contact-handled nature of the proposed Hanford FBSR LAW would not require remote systems for repairing and replacing equipment in a heavily shielded environment, which has caused limitations for IWTU. The large and extensive treatment system represents an interdependent and complex system. The offgas system is similar to IWTU (without scrubber) and variations have been tested extensively in previous pilot-scale test rigs. The proposed FBSR for Hanford LAW is simpler in that a TO would be used instead of a CRR, which was troublesome during IWTU startup and had refractory issues (Farnsworth et al., 2019). A single unit operation failure in the system will slow or delay operations or even shut down the system. Consequence: Challenging to run system, delayed processing, additional costs, missed milestones.

3.1.1.2.1. Unit operations (21 systems listed below)[6]

- Feed preparation tasks
  - Clay feed system
  - Waste staging, mixing feed system (moderate complexity)
  - Additive feed system
  - Gas supply systems
- FBSR system
  - DMR (high complexity)
  - Spray nozzles (moderate complexity)
  - Process gas filter
  - Steam supply

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[6] Very low or low complexity/consequences unless specified otherwise.

- Offgas system
  - Thermal oxidizer
  - Cooler
  - Carbon bed
  - Wet scrubber (if needed)
  - Reheater
  - Pre and HEPA filters
- Solids handling
  - Product handling system (moderate complexity)
  - Geopolymer additive system
  - Geopolymer mixer
  - Geopolymer product packaging
  - Geopolymer storing/curing
  - Container swabbing and decon station
  - Container load out station.

3.1.1.2.2. Accuracy of controls needed

- Sampling/measurements needed to control process – Very high complexity. Batch qualification is expected to give composition for clay/alumina amount where clay content and type are adjusted to account for alumina in the LAW (SRNL-STI-2011-00387). Process variability vs. clay/alumina composition and operating conditions has not been tested for a designated set of waste compositions to consistently achieve an acceptable crystalline structure (e.g., sodalite and nosean may form a solid solution; however, they are isostructural and contain a cage that could isolate CoCs). Consequence: Potential low throughput; poor product quality.

- Modeling needed to control process – Very high complexity. The FBSR process is driven by compositional requirements to produce a durable waste form (equivalent to the Na_2O-Al_2O_3-SiO_2 chemistry "shown to be acceptable" in 2001 with Tank AN-107 simulants) that is flowable, free of secondary phases, and of reliable durability. Reactions in the DMR gas phase occur within seconds, requiring a constantly vigilant process control system. Consequence: See items below. After solid phase measurements have confirmed inferences from leaching data of structural incorporation of ^{99}Tc and ^{129}I (with additional, supporting lines of evidence) and reoxidation of the granular waste form has been evaluated, a defensible product control system that accommodates variabilities and uncertainties in inputs (e.g., feed compositions), clay additives, etc. could be developed using the MINCALC™ system as a reasonable starting point.[7]
  Expect FBSR is moderately robust toward composition and operation with few parameters needed. Testing assumed during development would be used to develop/refine models/control process.
  - Failure modes for improper operation
    - Improper mineralized product production

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[7] The evaluation of the long-term performance of the resulting steam reforming products (e.g., in a PA) would benefit greatly from additional information on the thermodynamic and rate model parameters needed to represent the dissolution of the steam reforming waste form in a PA to calculate a fractional release rate.

    - Producing wrong mineral product or an amorphous product due to inability to control additives and process conditions would impact leachability and long-term performance of the radionuclides and metals from the waste form product.
  - Off-normal waste feed composition
    - Variations in ratios of concentrations of elements captured in the primary waste form (e.g., sodium, chromium, halides, radionuclides) and their potential interactions can lead to variations in the primary waste form chemistry and mineralogy that may impact waste form performance.
  - Improper coal/oxygen addition
    - Excess coal/insufficient oxygen addition causes higher levels of unreacted coal in the primary waste form and operating changes in the TO.
    - Insufficient coal/excess oxygen causes incomplete nitrate/NO_x destruction.
  - Improper clay addition
    - Improper amount of clay results in inadequate mineral product formation, or higher volumes of primary waste form. Note that most of the pilot-scale studies were run using excess clay; however, subsequent BSR testing demonstrated that excess clay was not needed…[and helps] maximize Na_2O waste loadings (SRNL-STI-2011-00387 [p. 53]).
  - Failure to control key temperatures in the DMR, PGF, TO, and offgas system
    - Temperatures too low could cause off-specification mineralized product, incomplete nitrate/NO_x destruction, incomplete organics/H_2 destruction, particulate filtration failure, or creation of aqueous secondary condensate.
    - Temperatures too high could cause filter failure, refractory failure, higher NO_x emissions, DMR slagging or fouling/scaling.

3.1.1.2.3. Commercially available/similar (of a type) to available/bespoke systems – High number of custom components. The supplemental LAW FBSR facility would be first-of-a-kind, but some components are used in related or other systems in use (e.g., product handling and packaging system, PGFs, GAC bed, and process blowers at IWTU). Thus, many of the IWTU lessons learned would be applicable, including ceramic PGFs and nozzle design. Entirely or relatively new for this application: DMR producing durable mineralized product; spray nozzles for an alkaline clay slurry; product handling system; configuration and integration of offgas system, geopolymer monolithing system; (and perhaps refractory lining of DMR). Consequence: Need to redesign/rebuild, causing mission delays.

3.1.1.2.4. Overall flowsheet integration complexity – Very high overall complexity. The flowsheet for an FBSR facility for supplemental LAW treatment is more complex than for a grouting facility and of similar complexity when compared to vitrification. The waste feed system includes batch analysis and metered addition of clay based on the feed analysis to produce the desired mineralized waste form with highest practical waste loading.

Multiple waste feed nozzles are used to feed the DMR, which has several other gaseous (steam, nitrogen, oxygen) and solid (coal) inputs; the feed rates of which must be controlled to maintain DMR operation within fluidized bed hydrodynamic and stoichiometric limits.

The mineralized product handling system includes equipment for collecting, pneumatic transferring, and cooling the mineralized product so that it can be formed, with geopolymer additives, into the geopolymer monolith product, in containers for storage, transport, and disposal.

The offgas system includes high and low-temperature (HEPA) filtration, thermal oxidation, GAC bed mercury absorption, wet scrubbing, and offgas cooling and reheating. The recycle of spent scrubber solution to the feed system can tolerate some additional variability to the waste feed composition that must be accounted for in the feed analyses and clay additive determinations.

Operating experience from WTP LAW Vitrification Facility will help with some design and operation that FBSR has in common with vitrification, including waste feed staging and mixing, the carbon bed, and HEPA filtration. IWTU operating experience will help with the DMR, PGF, product handling system, offgas cooler, carbon bed, and HEPA filtration. Industrial and commercial operating experience in other industries will help with design and operation of some FBSR unit operations, including liquid, solid, and gas transport (feed and product systems), product monolith (grouting) system, product storage and curing, and thermal oxidation. Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition. Mitigated by experience at IWTU and years of testing assumed performed prior to construction.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed) – FBSR requires extensive utilities, including large demands for steam, cooling water, liquid oxygen, and liquid nitrogen, and process chemicals such as clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH).

Operating experience from IWTU, presuming it continues on its startup/operation path, would be applicable for all of this infrastructure except for the clay additive, TO fuel, and geopolymer additives. The infrastructure for the clay, TO fuel, and geopolymer additives is similar to relevant infrastructure in other industries. Cross-site supernatant liquid transfer line is needed to support this alternative.

Consequence: Delayed processing, complex interrelated systems, DMR idling causing variability in waste form composition due to addition of alumina (if the DMR is idled for 1-2 days based on IWTU experience but perhaps longer for the mineralized product) and continued addition of coal/oxygen/steam to maintain bed fluidizing; also causes attrition of particles in bed. If shutdown is required, can impact schedule and primary waste form properties. Further risk mitigation is provided in planned process demonstration at pilot- and demonstration-scale prior to full-scale supplemental LAW treatment system design.

3.1.1.4. Required demolition/removal/modification – It is expected that siting will not require demolition or removal of existing facilities. No consequences.

3.1.1.5. Technology maturity, including Test Bed Initiative
[MOE: Being completely ready to requiring development to make process work.] – Some aspects demonstrated. The FBSR alternative will use a new flowsheet and approach. Portions of the process have been tested using pilot- and full-scale systems. Uncertainty remains in the partitioning of selected species and in the long-term performance of essentially every FBSR unit operation which, while represented in other systems – including the WTP LAW melter systems and IWTU, Irwin, and pilot-scale simulant testing – will need to operate with the specific design and operation for supplemental LAW treatment. Consequence: Delayed processing and higher costs due to either process stoppage for redesign and process changes, or to more frequent or longer downtime for maintenance.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list) [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Low robustness. Recovery actions from things that go wrong include slowing or stopping the feed while performing corrective actions, process shutdown for redesign and process changes, or more frequent or longer downtime for maintenance. Based on prior FBSR experience at IWTU, unit operations most prone to failure or at least frequent maintenance include the feed systems, PGF, and product handling system. Consequence: Delayed processing and higher costs. Some mitigation by pilot-scale testing that would be performed prior to final design and operation.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form from IDF with current techniques, place the waste form in HICs, or better isolate the waste form in IDF. Consequence: Retrieve the containerized material for alternate disposal or add an additional robust cap (for example) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions and flowrates
[High heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – Moderate adaptability. The ability to adjust waste loading and clay/alumina amounts (where clay content and type are adjusted to account for aluminum in the LAW feed) would allow an FBSR facility to handle a wide range of feeds. NRC (2011) concludes "…crystalline ceramic waste forms produced by FBSR have good radionuclide retention properties and waste loadings comparable to, or greater than, borosilicate glass."

However, the Hanford LAW compositions tested to date do not adequately represent those likely to be treated and more work (e.g., based on designed experiments) would help demonstrate process capability. Non-pertechnetate is not an issue for the FBSR process since any non-pertechnetate would likely react to form Tc(VII) in the DMR. Consequence: Delayed processing and higher costs. Mitigated by ability to analyze and blend waste feed in the feed system, use of two FBSR systems where one could be shut down for maintenance or during times of reduced demand.

3.1.4. Ability to incorporate future advances

[MOE: Easily incorporated to impossible.] – Moderate adaptability. The high capital cost and unique operations makes incorporation of future advances challenging. Consequence: High cost of changes.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.] – FBSR uses commonly available feed and start-up bed materials – water, steam, clay, coal, alumina, TO fuel (propane, natural gas, or fuel oil), sulfur-impregnated activated carbon, HEPA filters, and geopolymer additives (clay, sodium silicate, and NaOH). These are all common commercial and industrial materials. The likelihood of failure to resource constraints is low. The consequence of failure due to a constraint on any one of more of these materials is also low. For example, if one coal or clay becomes unavailable, then another of many other coal and clay options that have already been studied could be used. If one fuel for the TO becomes unavailable, other fuel options, some already studied, could be used.

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – The funding needs for a supplemental LAW FBSR facility will likely exceed the annual benchmark funding for a supplemental LAW treatment facility ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW only) against benchmark annual supplemental LAW treatment budget] – The peak funding needs for a supplemental LAW FBSR facility will likely greatly exceed the benchmark funding level for a supplemental LAW treatment facility ($450M/yr).

3.2.3. Schedule flexibility – ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] – FBSR facilities can operate at perhaps ~10–20% of the design feed rate, but have limited ability to operate at lower rates. Idling the DMR at temperature with no waste feed is practicable for up to ~1–3 weeks but would require adding fluidized bed media to account for attrition and would cause contamination of the treated product with non-rad added bed media. The steam reforming equipment can be powered down almost instantaneously. The cold shutdown time for the Hanford LAW FBSR would be controlled by the cool down rate for the DMR because a TO would be used. Based on IWTU experience, it would likely take 2-3 days to go from operation for cold shutdown for the proposed Hanford LAW FBSR facility. Startup taking ~1-2 weeks would be a reasonable estimate for the proposed Hanford LAW FBSR facility. Using two FBSR facilities provides more flexibility than one because one or both can be operated at higher or lower feed rates, on idle (for up to about 1-3 weeks, or shut down, to match changes in feed supply.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – High potential failure is assumed to be caused by a lack of funding, and the failure point would occur during construction at peak spending. Consequence: Delayed mission due to lack of funding, delayed start of supplemental LAW treatment processing. Moderate amount of funding spent and time consumed prior to funding failure.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the facility starts and stops prior to startup. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to FBSR option, construct, and then funding is not allocated for startup. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones.

3.3. Likelihood and consequences of failing to complete due to **unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).] – The supplier used for the FBSR is a single U.S. vendor that could go out of business. Consequence is DOE would assume the technology ownership and continue operations, potentially causing additional cost and delays. Calcined coal is typically added directly to the DMR bed as a fuel source and a reductant (SRNL-STI-2011-00387); however, the calcined coal used in IWTU has a single source in China. This supply chain should be evaluated if FBSR is selected for Hanford supplemental LAW treatment.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. (All costs are discounted at 3% rate.)

Total: $5,527 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$3,375 M (includes commissioning costs)

4.2. Operations costs

$2,152 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

C.2.12 Selection Criteria Assessment for Alternative Grout 4B

Alternative Grout 4B: Off-site Vendor for Grouting with Off-site Disposal

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

Note: This evaluation assumes that the vendor performs the grouting process (i.e., it is essentially identical to Grout 1B alternative in operations and product, and only differs in location of the immobilization step).

1. Long-term effectiveness

(environmental and safety risk after disposal)

1.1. *Residual threat to health and environment upon successful completion*

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents – to all retained–to–amount increased by treatment.]

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; all alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over the long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for the long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for the long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides
[MOE: Estimated peak groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).]

1.1.2.1.1. Iodine – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.2. Technetium (non-pertechnetate will be evaluated below in confidence) [MOE is projected concentration in groundwater.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site. BFS sequesters technetium.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1 compliance period); identify peak to 10,000 years to address longer-term groundwater protection.] – No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.1.2.3. Ammonia [No MOE needed; no differences between alternatives; ammonia stripped during evaporation is immobilized at ETF.] – Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives. No significant amount of residual ammonia in grouted tank wastes. Minimal impact to Hanford groundwater due to grouted ETF solids from on-site supplemental LAW evaporator. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements. Ammonia from this option is low in the grouted secondary waste disposed of in IDF, but ammonia will still be present from LAW melter system so is not differentiating among alternatives.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP, which reducing grout consistently passes. Grout waste form will be TCLP compliant (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium – Cr(VI) sequestered by redox reductants in BFS and precipitation as hydroxide with alkali. Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed.] – Grout waste form will be TCLP-compliant (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] – Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include the evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS.

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentrations of LDR organics in the waste. High confidence LDR organics are not present above limits or can be removed/destroyed to beneath regulatory limits if needed (RPP-RPT-64064, *Distribution of LDR Organic Compounds in Hanford Tanks Waste and the Implications to LAW Treatment by Cementitious Solidification/Stabilization*); additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

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[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.2. Technetium (including non-pertechnetates) – High confidence in speciation in waste as predominantly pertechnetate with a small fraction of non-pertechnetate in most tanks. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.3. ^{79}Se – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting their license requirements.

1.2.2.4. Nitrates/nitrites – No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP/waste acceptance criteria.

1.2.2.6.3. Other RCRA metals – High confidence in ability to pass TCLP/waste acceptance criteria. Moderate confidence on speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria.

1.2.3. Confidence in total volume of primary and secondary waste forms produced

High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. *Specific risks or benefits related to ongoing tank degradation* – Remove waste earlier to minimize leak risk.

[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~5 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~5 years has moderate risk of additional tank leaks since retrievals would be on schedule to support HLW, allowing limited time for corrosion-induced leaks. This alternative keeps HLW processing on schedule.

Continuity of operations after startup – loss of specific DSTs is less impactful because it does not rely on the cross-site transfer line and is more flexible in specific feed piping, tank utilization, etc. As this applies to both 200 West and East Area facilities, it is less directly dependent on specific infrastructure, including DSTs, and would therefore be less impacted by failure of key staging and transfer tanks.

This alternative does not consume the entire initial benchmark supplemental LAW treatment budget, providing an opportunity for an early start as part of a hybrid or concurrent alternative treatment, so there is potential for reducing the risk of tank leaks. (See hybrid alternatives description.)

2.2. *Risks to humans (other than tank degradation)*

2.2.1. Effort required to ensure worker safety

[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporizing of radionuclides. Some construction near an operating radioactive facility. Some worker exposure to radioactive liquids due to loading/unloading liquid in truck.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Very low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabricated hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (High consequence hazard is not applicable to this alternative since there is no vault.) Over 20 years of operation of saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)] – Moderate risk. High number of radioactive transports. No transports of raw materials onto site; no hazardous liquid chemicals shipped onsite; many radioactive liquid transports of treated supplemental LAW offsite; radioactive liquid transport of evaporator condensate to ETF (assumed to be by truck); many off-site transports of solid radioactive materials (grouted waste) from vendor to off-site disposal facility.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to high discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; evaporator condensate collected to LERF/ETF (~38% of feed volume[2]) containing radioactive and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases possible; evaporator condensate is collected; HEPA/GAC-filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Few tanks and process unit operations onsite. Risk of liquid spills during transport of both supplemental LAW to off-site vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to high risk for off-site spills.] – Low risk of liquid spills during transport of liquid decontaminated supplemental LAW to off-site vendor.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid and solids and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment].] – Minimal solid waste; some equipment and job control waste. Evaporator condensate to LERF (380,000 gallons per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions

[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gallons of boiler fuel oil for LDR evaporation (total of ~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals, assuming that the vendor requires the same amount of electricity and grout formers as was calculated for the Grout 1A alternative (RPP-RPT-63426).

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[2] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

There would be additional emissions from transport of liquid to the vendor and then shipping offsite. Expect shipments of ~46,000 grouted waste form boxes to distant disposal location(s) (see Volume II, Section H.9 for more information).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~5 years – Vendors are available with the ability to perform this operation with existing facilities. Time to startup will be a function of the readiness of the Hanford Site to ship material to the vendor and the permitting required to process and dispose of the waste.

2.4.2. Duration to full capacity (additional years) 0 years – Vendors are available with the ability to perform this operation with existing facilities.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risks of additional mission delays.

2.4.4.1. Delays due to technical/engineering issues – Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk that LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*),and mitigation is to send noncompatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Very low risk of delay. Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities expected to not extend duration of supplemental LAW and HLW processing.

3. Likelihood of successful mission completion
(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: Technology failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed of waste). [MOE: Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences.] – The grout alternative will use the same flowsheet and approach as the existing SRS facility. Formulations will vary somewhat, but engineering uncertainties are minimal. Uncertainty remains in LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence is reduced waste loading or diverting more waste to LAW melters or vendor treatment.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (by changing grout or GFC recipe, etc.) – Low likelihood of failure and low consequences. It is expected that a grout process will be able to produce an acceptable grout from the entire waste feed vector and the ability to quickly restart from a cold shutdown provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives, reduced waste loading.

3.1.1.1.2. Transport lines become blocked/congested or leak – Low likelihood. Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.3. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidization methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Mitigation is potential for off-site vendor treatment.

3.1.1.1.4. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk. The LDR organics are assumed to identified during batch qualification and detection limits can be reached. Consequence: Concentration of organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk; top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.).] – Low complexity. Grouting of the supplemental LAW feed requires few integrated unit operations. The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations[3]

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment – Metered additions, mechanical mixing, potential offgas generation.

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[3] Very low or low complexity/consequences, unless specified otherwise.

- Receipt/storage tank (agitated, cooled?) – Vessel with pumps.
- Receipt tank (agitated, cooled?) – Continuous stirred tank reactor vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment – Hoist and forklift operations.
- Container box disassembly and emplacement at off-site location(s) – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition. Moderate consequences.
    - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-specification composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed overcapacity design of system, lessons learned from SRS or other sites. The use of an off-site grouting facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduces SST leakage risk; reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Only building Tank Farms Pretreatment (TFPT)/LDR evaporator and liquid load-out facility onsite.
- Utility usage (electrical, cooling water, steam, etc. is low).

- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed.

3.1.1.5. Technology maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Grout in general is demonstrated; saltstone at SRS (similar process, scale, and waste operations since 1990), INL, etc. (including containerized grout). Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for Defense Waste Processing Facility [DWPF] effluents). Alternative assumes that vendor can produce viable waste form. Consequence: Additional development time needed, delayed processing. Moderate consequences.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Highly robust. Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized. Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – Very high robustness. If future information indicates unexpectedly poor waste form performance, it could be necessary to remediate the waste form. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (for example) or barrier or other technology may be an alternative. Low consequences.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – High adaptability. Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, etc.). Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – High adaptability. Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Unlikely vendors need to expand capacity but expect that vendors could handle variability in flow rates so expansion unlikely to be needed. Some vendors may need permit changes. Consequence: Minimal cost and short delays.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending

[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The funding needs for off-site immobilization will likely be beneath the annual spending benchmark funding level ($450M/yr).

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget.] – Low likelihood of failure. The peak funding needs for off-site immobilization will likely be beneath the benchmark funding level ($450M/yr).

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] Very high flexibility. Grout facilities are typically able to operate beneath maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] Scenario is operations more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and need to select alternate solution. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Operation does not start or stops until funding is available. Start of supplemental LAW treatment mission is delayed. Worst case is to commit to grout option and then funding is not allocated. Consequence: Delay of initiation of supplemental LAW immobilization, which may result in additional tank leaks and missed milestones. Sufficient funds would likely be available to perform this alternative by the project need date.

3.3. Likelihood and consequences of failing to complete due to **unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production.] Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only (e.g., off-site vendor; special ingredient; sole source provider). – Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. If the vendor is unable to perform the task, another vendor could be selected.

Off-site disposal location could cease receipt of waste or permission to transport is revoked for unforeseen reasons. Consequence: The process impact would be a delay in processing until an alternative is identified or if an ingredient cannot be procured and one has not been pre-selected.

Limited use of sampling since the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process. A ~2.5-month working inventory of material would remain onsite at the vendor or in-transit until the issue is resolved (maximum of 750 containers).

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. All costs are discounted at 3% rate.

Total: $3,854 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$410 M (includes commissioning costs)

4.2. Operations costs

$3,444 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

C.2.15 Selection Criteria Assessment for Alternative Grout 6

Alternative Grout 6: Phased Off-site and On-site Grouting in Containers

Color key:

- Criteria to be assessed
- Assumptions and ground rules; measures of effectiveness (MOE)
- Assessments and comparative notes
- Assessment description
- Notes and referrals to other sections

1. Long-term effectiveness
(environmental and safety risk after disposal)

1.1. Residual threat to health and environment upon successful completion

Assumption: Only alternatives assessed as likely to comply with anticipated regulations and applicable standards for mobility and toxicity of wastes at project completion were fully evaluated for comparison. Alternatives unlikely to comply with one or the other will be screened out.

1.1.1. Residual toxicity of wastes [MOE: All material destroyed to non-toxic constituents - all retained – to amount increased by treatment.] – Applicable to all three phases.

1.1.1.1. Nitrates/nitrites [MOE is nitrate/nitrite (as nitrogen) DWS for leaching during disposal in IDF PA.] – High residual toxicity. No reduction in inherent toxicity vs. feed vector.

1.1.1.2. RCRA metals – High residual toxicity. No reduction in inherent toxicity; All alternatives are equivalent.

1.1.1.3. LDR organics – Low residual toxicity. Negligible; any waste not sufficiently treated by evaporators/oxidation will be sent to vitrification. Organics removed from waste treatable at LERF/ETF.

1.1.1.4. Ammonia – Low residual toxicity. No significant amount of residual ammonia in grouted tank wastes over long term.

1.1.1.5. Greenhouse gas emissions – No residual greenhouse gas/carbon footprint differences (from final waste form(s) after disposal) across alternatives for the long term; non-discriminatory. Greenhouse gas emissions are greater during construction and operations (see Section 2.3.6). [No MOE needed for long term.]

1.1.2. Mobility of primary and secondary wastes to a groundwater source (given intended disposal site(s))

1.1.2.1. Radionuclides [MOE: Estimated peak groundwater concentration at compliance point over ~1,000 years (e.g., DOE O 435.1; IDF PA compliance point and period); identify peak to 10,000 years to address longer-term groundwater protection (e.g., post-compliance period).]

1.1.2.1.1. Iodine – Onsite: Iodine mobility to ground water is limited during the first 1,000 years compliance period. Iodine sequestered by getter leads to enhanced retention in waste form; relative to non-getter waste form. Projected ~100× below DWS (maximum contaminant level) per NDAA17 report but uncertainty in long-term performance with only laboratory data to date. Iodine not bound to getter could exceed DWS.

To limit mobility beyond the period of compliance, iodine requires stability of getter phase to meet concentration limits.

On-site inventory from supplemental LAW reduced by ~50% or more. Inventory remaining onsite is assumed to scale proportionally to peak dose at point of compliance. Offsite: No impact to Hanford groundwater due to disposal of primary waste form offsite. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.2. Technetium – Onsite: Technetium mobility to ground water is limited during the first 1,000 years (compliance period) due to facility performance. BFS sequesters technetium providing high performance for technetium; ~10× below DWS per NDAA17 report; uncertainty in rate of reoxidation of grout in IDF; an oxidized grout could exceed DWS. To limit mobility beyond the period of compliance, technetium requires maintaining reducing conditions for a portion of the waste form during disposal to meet concentration limits. This behavior is required for the primary supplemental LAW grout and the secondary waste grout. On-site inventory from supplemental LAW reduced by ~50% or more. Inventory remaining onsite will scale proportionally to peak dose at point of compliance. (Non-pertechnetate will be evaluated below in confidence.) Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste attributes will comply with the current waste acceptance criteria for the disposal site.

1.1.2.1.3. Selenium-79 (^{79}Se) – Sequestered by waste form. Minimal impact due to limited quantity (114 Ci, see Volume II, Section E.3.1.3). On-site inventory reduced by this alternative. Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.1.2.1.4. Cesium and strontium
[Cesium and strontium half-lives make them short-term only issue; no MOE needed.]

1.1.2.2. Nitrates/nitrites [MOE is estimated peak nitrate/nitrite (as nitrogen) groundwater concentration at IDF PA compliance point over ~1,000 years (to DOE O 435.1; IDF PA compliance period); identify peak to 10,000 years to address longer-term groundwater protection (post-compliance period).] – Onsite: Nitrate/nitrite mobility to groundwater is limited during the first 1,000 years compliance period. Retained only by diffusion barrier (physical entrapment). Recent diffusivity testing shows some formulations can retain nitrate/nitrate more effectively and estimate peak concentrations below the compliance standard. These tests were performed in a conservative, saturated environment, which would produce much greater release rates than actual unsaturated conditions in the IDF.

Conservative assumptions regarding nitrate/nitrate subsurface behavior could result in exceedance of DWS (PNNL-28992, *Performance Metric for Cementitious Waste Form Inventory Release in the Integrated Disposal Facility*, Figure 4-3). On-site inventory reduced by this alternative in roughly the same fraction as the disposed volume.

Offsite: No impact to Hanford groundwater due to off-site disposal. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting the site's license requirements.

1.1.2.3. Ammonia – Onsite: No significant amount of residual ammonia in grouted tank wastes. [No MOE needed; ammonia stripped during evaporation is immobilized at ETF.] Ammonia from this option is low in the grouted secondary waste disposed of in IDF but ammonia will still be present from LAW melter system so is not differentiating among alternatives. Offsite: Minimal impact to Hanford groundwater due to grouted ETF solids. Off-site disposal sites do not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site, which ensures meeting the site's license requirements.

1.1.2.4. RCRA metals [MOE is leachate TCLP compliance.] – Mobility judged against TCLP, which reducing grout consistently passes. Onsite: Waste form has reduced toxicity. Grout waste form would be compliant. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.1. Mercury [MOE is retention of mercury in primary vs. secondary waste form.] – Sequestered by sulfide reaction with BFS and low inventory. Onsite: Sequestered by sulfide reaction with BFS. Offsite: Grout waste form will pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.2. Chromium [MOE is retention of chromium in waste form (grout redox chemistry).] – Onsite: Cr(VI) sequestered by redox reactions with reductants in BFS and precipitation as hydroxide with alkali. Uncertainty exists in rate of reoxidation of grout in IDF and change in waste form pH; an oxidized, neutral grout could exceed DWS for chromium. To limit mobility beyond the period of compliance, chromium requires maintaining reducing conditions for a portion of the waste form and maintaining alkaline conditions during the disposal to meet concentration limits. Alkaline conditions projected to persist well beyond the period of compliance. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.2.4.3. Other [No MOE needed.] – Onsite: Projected concentrations of other RCRA metals (e.g., lead) appear not to exceed DWS limits and are significantly beneath concentration of chromium. Offsite: Grout waste form would pass TCLP (RCRA), which is required to satisfy the disposal site waste acceptance criteria.

1.1.3. Total volume of primary and secondary waste forms
[MOE is volume of primary and all secondary waste forms.] Primary waste form is high with 1:1.8[1] volume increase (same as in NDAA17 report) for the waste after evaporation. Secondary solid waste volume is minimal. WRPS calculated that for 1 gallon of LAW feed: 1.6 gallons of primary waste grout and 0.017 gallons of solid waste (RPP-RPT-63426, *Calculating the Non-Monetary Impact of Operating a Grout Facility*). However, the reference did not include the evaporation step, which would add ~0.38 gallons of liquid effluent disposed of at SALDS. Onsite: Total volume remaining onsite reduced by 30% or more.

1.2. Long-term risks upon successful completion

[Exogenous risks (e.g., earthquake, catastrophic flood, volcano) are assessed as indistinguishable across all technologies and disposal locations.]
[MOE: Error bars in estimates vs. margin under health/regulatory standards.]

1.2.1. Confidence in estimated residual toxicity [MOE: High confidence in value to low confidence.]

1.2.1.1. LDR organics – Moderate uncertainty with the concentration of LDR organics in the waste. High confidence LDR organics are not present above limits or could be removed/destroyed to beneath regulatory limits, if needed; additional evaluations, analyses, and testing planned; alternative is sending to LAW vitrification.

1.2.1.2. Nitrates/nitrites – High confidence in no change to toxicity.

1.2.1.3. Ammonia/ammonium ion – High confidence that ammonia will not be significant in grouted tank waste. Tank waste only contains small amounts of ammonium ion, which will be vented during evaporation and/or grout formation.

1.2.1.4. RCRA metals

1.2.1.4.1. Mercury – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.2. Chromium – High-moderate confidence in no change to toxicity. Oxidation state and speciation could change vs. current state.

1.2.1.4.3. Other RCRA metals – High confidence in no change to toxicity.

1.2.2. Confidence in immobilization with respect to groundwater

1.2.2.1. Iodine – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and in the resulting waste form as iodide with a fraction of iodate. Moderate confidence in the immobilization of AgI from reaction with getter in the waste form, but any unreacted free iodide/iodate would be mobile. Success of the silver precipitation approach has been shown at the laboratory-scale using getters but not demonstrated at pilot- or process-scale.

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[1] Bounding case of 1.8 ratio per p. A-22 from DOE/EIS-0082-S2, *Savannah River Site Salt Processing Alternatives Final Supplemental Environmental Impact Statement*, (and confirmed [as nominally 1.76 gallons of grout per gallon of feed] by recent operating experience at the Saltstone Disposal Facility from SRR-LWP-2009-00001, *Liquid Waste System Plan* [pp. 18, 36, and 40]); DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC & WM EIS) provides a value of 1.4× (p. 2-28); range is 1.4–1.8.

The immobile fractions as AgI can destabilize with time due to chemical reduction of Ag^+ to Ag^0 and competition with other species (e.g., sulfide that can form Ag_2S), the rate of these destabilization processes in the disposed waste form is untested. Iodine is a key constituent of interest in the IDF PA.

^{129}I can define waste classification but concentrations in Hanford tanks are likely far lower than Class A limit.[2] Once released by chemical reactions and leached into the subsurface, there is limited to no natural attenuation of iodide, and as such the supplemental LAW iodine inventory could impact groundwater limits in the post-compliance period. However, a complete assessment of iodine impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.2. Technetium (including non-pertechnetates) – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste as pertechnetate with a fraction of non-pertechnetate. Within the waste form, there is high confidence in the conversion of pertechnetate to a reduced and insoluble technetium, but there is an unknown behavior of non-pertechnetate. High confidence in initial immobility of reduced technetium. The reduced, insoluble technetium in the waste form could be destabilized with time due to oxidation but the rate of reoxidation under the proposed Hanford disposal conditions is unknown. Technetium is a key constituent of interest in the IDF PA. Technetium can define waste classification and select tanks have technetium concentrations that approach the Class A limit.[3] However, a complete assessment of technetium impact in the post-compliance period must be evaluated in a PA considering multiple variables (inventory, waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.3. ^{79}Se – Limited to no data available on the speciation in the waste, in grout, or mobility within grout waste forms. Limited attenuation in the Hanford subsurface. High confidence of minimal impact due to minimal inventory (144 Ci or ~2 kg per RPP-ENV-58562, *Inventory Data Summary for the Integrated Disposal Facility Performance Assessment*). Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

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[2] ^{129}I is listed in Table 1 of 10 CFR 61.55, Waste Classification, that is used to classify wastes for near-surface disposal. Class C limit for ^{129}I is < 0.08 Ci/m^3, Class A limit < 0.008 Ci/m^3.

[3] ^{99}Tc is listed in Table 1 of 10 CFR 61.55 that is used to classify wastes for near-surface disposal. Class C limit for ^{99}Tc is 3 Ci/m^3, Class A limit is 0.3 Ci/m^3.

1.2.2.4. Nitrates/nitrites – Onsite: High confidence in immobilization and limited impact to groundwater during the compliance period. High confidence in speciation in waste and waste form as nitrate/nitrite. Both nitrate and nitrite are not retained in grout waste forms and will not be slowed without formulation modification. Nitrate and nitrite are a key constituent within the IDF but will not drive waste classification or waste acceptance criteria.

There are no attenuation mechanisms within the disposal facility and only biological activity in the subsurface to slow migration. The nitrate/nitrite inventory is ubiquitous across the Hanford tanks, and a recent assessment projected concentrations slightly above groundwater limits in the post-compliance period using a projection of a non-optimized grout waste form disposed of in IDF (under saturated, non-conservative conditions resulting in higher than expected release).

As such, there is uncertainty in the overall impact to groundwater. A complete assessment of nitrate/nitrite impact in the post-compliance period must be evaluated in a PA considering multiple variables (waste form performance, infiltration rates, subsurface behavior) and important uncertainties. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.5. Ammonia/ammonium ion – Onsite: High confidence that grouted tank waste will not be a source of significant leaching of ammonium ion due to low concentration. Small amount of ammonia in ETF secondary waste grout disposed of in IDF poses minimal impact. Offsite: No impact to Hanford groundwater. Off-site disposal site does not have a pathway to potable water due to their geology. The immobilized waste will comply with the waste acceptance criteria for the disposal site.

1.2.2.6. RCRA metals

1.2.2.6.1. Mercury – High confidence in ability to pass TCLP, high confidence in ability to sequester due to mercury sulfide formation, but low confidence in mercury speciation in tank waste. High confidence in limited subsurface transport and limited knowledge on speciation changes in subsurface.

1.2.2.6.2. Chromium – High confidence in ability to pass TCLP due to sequestration by reduction to insoluble form by reaction with slag in waste form. Moderate uncertainty in reoxidation/solubilization rate in Hanford disposal environment and high confidence in knowledge of subsurface mobility; there is limited attenuation in the IDF backfill and subsurface although some mineral interactions (e.g., iron, carbonate, barium) have been observed. Chromate is slow moving in subsurface and expected to be compliant with DWS.

1.2.2.6.3. Other RCRA metals –. High confidence in ability to pass TCLP. Moderate confidence of speciation in waste and resulting waste form due to limited data. The use of slag and resulting high pH in cement-containing waste form serve to suppress migration of RCRA metals. Formulations to date have been successful in passing TCLP to assess RCRA behavior in waste acceptance criteria. Some species may have natural attenuation in the subsurface. Based on data to date, waste form is likely to pass TCLP; however, if Ag is added as iodine getter, this adds uncertainty.

1.2.3. Confidence in total volume of primary and secondary waste forms produced
High confidence in predicted total volume of primary waste and minimal secondary waste volumes.

2. Implementation schedule and risk

(environmental and safety risks prior to mission completion, including risks driven by waste tank storage duration)

2.1. Specific risks or benefits related to ongoing tank degradation – Remove waste earlier to minimize leak risk.
[MOE is time to start and processing duration. Risk of tank leaks for both DSTs and SSTs is based solely on time before waste is retrieved and processed because of continued tank corrosion during waste storage.] (See tank leak discussion in Volume I, Section 1.3.3 for more detail.) – Startup in ~5 years, short ramp up to full processing rate, high flexibility in rate, high throughput/TOE, simple and common components, low maintenance needs, and minimal secondary waste handling reduce delays and therefore lower risk of additional leaks. Startup of this process in ~5 years has lower risk of additional tank leaks because retrievals would be earlier than currently scheduled and would support HLW, allowing the lowest time for additional corrosion-induced tank leaks. This alternative would keep HLW processing on schedule.

Continuity of operations after startup – depending on when an unforeseen event (e.g., tank leak) happens, loss of specific DSTs is more or less impactful. During the initial phase when liquid is shipped offsite, continuity is less dependent on infrastructure items, like the cross-site transfer line. But in later phases when operations transition to on-site production of grout, continuity is dependent on the cross-site transfer line, specific feed piping, tank utilization, etc. Since this has both 200 East and West Area facilities, continuity of operations is directly dependent on specific infrastructure, including DSTs, and would therefore be partially impacted by failure of key staging and transfer tanks.

This alternative is intended to consume the entire initial benchmark supplemental LAW treatment budget and takes advantage of the opportunity for an early start as part of a hybrid or concurrent alternative treatment. There is potential for reducing risk of tank leaks. (See hybrid alternatives description.)

2.2. Risks to humans (other than tank degradation)

2.2.1. Effort required to ensure worker safety
[MOE: No hazards requiring mitigation to multiple hazards requiring mitigation methods.]

2.2.1.1. Radiation – Low hazards. No vaporization of radionuclides. Some construction is near an operating radioactive facility (LAW Vitrification Facility); construction would have shorter duration intervals in comparison to other alternatives.

2.2.1.2. Chemical exposure – Low hazards. Negligible hazardous offgas; no toxic volatile or liquid chemicals. Minimal ammonia released during LDR removal. Strong caustic solution.

2.2.1.3. Particulate exposure – Low hazards. High volume of fine powder with various transport mechanisms has potential risk of worker exposure to silica and other particulates.

2.2.1.4. Physical injury – Low hazards. Low temperature; simple construction; largely off-site prefabrication hardware components. Some construction is near congested construction sites. Unmitigated hazard analysis indicates 12 events of moderate consequence to the facility worker due to chemical hazards (RPP-RPT-63426). (One high consequence hazard is not applicable to this alternative since there is no monolith in a vault). Over 20 years of operation of saltstone facilities at SRS demonstrates viable and safe performance at scale with comparable waste.

2.2.2. Transportation risks

[MOE: Number and distance of trips, nature of shipment – hazardous vs non-hazardous, non-rad vs rad. (MOE: Few trip/shipments to high number of shipments.)]
Large number of transports of raw materials onto site and waste form boxes onsite; large number of radioactive and hazardous liquid transports. Onsite: Large number of solid radioactive waste form packages. Offsite: Many off-site transports of liquid and/or solid radioactive waste form packages to distant location(s). Practical impact would be negligible because transport of low dose solid and liquid radioactive materials is well known.

2.3. Risks to the environment (other than tank degradation)

2.3.1. Wastewater discharges (intentional)

[MOE: 1. Volume of wastewater discharged, 2. Composition (chem and rad), 3. Are upgrades to ETF needed? (No discharge, no chem/rads, no upgrades to ETF to highest discharge volume, contains chem/rad, upgrades to ETF needed.)] – Minimal; all LAW/flush water during grouting is recycled into next batch; evaporator condensate collected to LERF/ETF (~38% of feed volume[4]) containing radioactive and hazardous constituents similar to existing discharges from 242-A Evaporator and is not expected to require ETF expansion. Tritium is sequestered in grout and will decay before contact with groundwater.

2.3.2. Atmospheric discharges

[MOE: Amount of radionuclides and CoCs released.] – Minimal releases likely; evaporator condensate is collected; HEPA/GAC filtered PVV. Low risk of inadvertent loss of contaminants to environment through evaporator. Abated stack emissions 8.72E-9 mrem per 1 Mgal of supplemental LAW. Negligible particulates from dry feed additions (per RPP-RPT-63426).

2.3.3. Transfer/process tank (on-site) spills (unplanned discharges)

[MOE: No risk of on-site spills to high risk for on-site spills (spill within facility not considered a spill for this category).] – Risk of liquid spills during transport of both LAW to off-site vendor and evaporator condensate to LERF/ETF. Mitigated by experience with shipment of radioactive liquids.

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[4] Assume LDR evaporation concentrates waste from 5.0 M [Na^+] to 8.0 M [Na^+].

2.3.4. Off-site transportation spills

[MOE: No risk of off-site spills to is high risk for off-site spills.] – Moderate risk of liquid spills during transport of liquid decontaminated LAW for off-site disposal. Large numbers of radioactive shipments, both liquid and (potentially) solids. Mitigated by experience with off-site shipment of radioactive liquids.

2.3.5. Secondary waste streams generated

[MOE: Volume of waste (liquid, solids, and equipment; low quantity of secondary waste to highest quantity of liquids, solids, and equipment] – Minimal solid waste; some equipment, HEPA/GAC filters, and job control waste. Evaporator condensate to LERF (380,000 gal per 1 Mgal of waste).

2.3.6. Greenhouse gas emissions

[MOE: Calculated fuel/power/deliveries.] – At a minimum, treatment of 1 Mgal of waste consumes ~30,000 gal of boiler fuel oil for LDR evaporation (~310 MT CO_2), 2.5 GWh of electricity, and requires 209 deliveries of grout formers and other process chemicals (RPP-RPT-63426). Offsite: Expect shipments of ~15,000 or more grouted waste form boxes to distant disposal location(s) (see Volume II, Section H.9 for more information).

2.4. Duration

2.4.1. Duration to hot startup (years from decision) ~5 years.

2.4.2. Duration to full capacity (additional years) 1 year.

2.4.3. Duration of operations (additional years) as needed to support HLW.

2.4.4. Risk of additional mission delays

2.4.4.1. Delay due to technical/engineering issues – Minimal risk to delay operations; technology is well understood and demonstrated successfully at full scale in DOE complex. Low risk LDR removal is not completely effective based on contemporary data and updated studies (SRNL-STI-2022-00391, *Organic Evaporation and Oxidation Testing in Support of Hanford Sample-and-Send*)and mitigation is to send non-compatible wastes to the LAW melter.

2.4.4.2. Delay due to annual operating costs exceeding budget – Simple system with demonstrated technology, low maintenance requirements, moderate operating duration, low temperatures, and minimal balance of facilities is expected to shorten the duration of supplemental LAW (and HLW) processing.

3. Likelihood of successful mission completion
(including technical, engineering, and resource-related risks)

3.1. Likelihood and consequences of failing to complete for technical reasons

3.1.1. Technology and engineering risk

3.1.1.1. Technology/engineering failure modes (Guidance: tech failure mode needs to include some identification of consequences and remaining waste/processing needed and rework of disposed waste) [MOE – Perceived likelihood of failure; low likelihood and minimal consequences to high likelihood and high consequences] Low risk. The grout alternative would use the same flowsheet and approach as the existing SRS facility. Formulations would vary somewhat, and getters would be included, but engineering uncertainties are minimal.

Uncertainty remains in the utility of getters at scale and LDR organic treatment, but the baseline process is considered robust to be able to immobilize the waste into a grout waste form. Consequence of failure to identify a suitable iodine getter or remedy results in failure in ability to dispose of waste onsite in IDF and shipping more waste offsite or to the LAW melters.

3.1.1.1.1. Ability to handle feed variability with changes to immobilization process (e.g., by changing grout or GFC recipe) – Low likelihood of failure and low consequences. It is expected that a grout process would be able to produce an acceptable grout from the entire waste feed vector and to restart quickly from a cold shutdown, which provides flexibility in handling large variations in feed volume. Consequence: Modification of grout additives and reduced waste loading.

3.1.1.1.2. Suitable getter (iodine and potentially technetium) not identified/long-term performance inadequate – Medium likelihood and high consequence for on-site disposal of grouted waste. While suitable getters for technetium and iodine have been tested in the laboratory, the application of these getters in a production process and in conjunction with each other has not been demonstrated. Consequence of not identifying suitable getters would be that on-site disposal of the grout is not permitted and other methods to sequester iodine (and potentially technetium) are not identified. Off-site disposal – getter/waste form performance not needed; very low risk.

3.1.1.1.3. Transport lines become blocked/congested or leak – Very low likelihood – Grout is a simple process with a small number of lines and lines are short. In addition, grout is an ambient temperature process with no heated process systems that could lead to drying the feed in the line. The simplicity of the facility would facilitate quickly identifying and repairing and process line issues. Consequence is replacement of piping.

3.1.1.1.4. Evaporation/oxidation does not adequately reduce feed LDR organics – Moderate uncertainty about the concentration of LDR organics in the waste and high confidence they are below limits or could be removed to be below regulatory limits, if needed. Studies indicate that most identified organics would be removed via evaporation and those not removed via evaporation may be treatable with low temperature oxidation methods. Consequence: If organics are identified in the feed that cannot be treated to beneath regulatory limits, the feed could be sent to the WTP LAW Vitrification Facility but impacts in process delays could occur. Mitigation is potential for off-site vendor treatment.

3.1.1.1.5. Sample analysis inadequate to allow sufficient feed to LDR treatment – Low-medium risk – The LDR organics are assumed to identified during batch qualification and detection limits can be reached for organics critical for assessing waste acceptance criteria. Consequence: Analytical methods may need to be improved for selected species.

3.1.1.2. Process complexity (flowsheet complexity risk) (top level view of flowsheet moving parts for large non-modular option)
[MOE: Unit operations involved and their complexities. (MOE: Low complexity to high complexity, total number of unit operations.) (Consider: Static versus moving components, temperature, reactions, gas phase formation/processes, mixed phase streams, number of process chemicals added, etc.)] – Grouting of the supplemental LAW feed requires few integrated unit operations.
The low temperature processing generates minimal offgas that requires filtration and perhaps GAC treatment prior to release. Minimal worker protections are needed to prevent exposure. The process contains few items that require routine hands-on maintenance or replacement. LDR evaporator is very similar to existing technology; LDR organic destruction, if needed, is TBD. Consequence: Delayed processing, additional costs, missed milestones. Mitigated by SRS operating experience providing input to operation and design and low operating cost per day.

3.1.1.2.1 Unit operations

- LDR organics evaporation/treatment (moderate complexity) – Assumes a recirculating vacuum evaporator – 50°C operation with phase change and condensate handling.
- Evaporator condensate system – Collection tanks, sampling, and pumps.
- Oxidative treatment (moderate complexity) – Metered additions, mechanical mixing, potential offgas generation.
- Receipt tank (agitated, cooled?) – Vessel with pumps.
- Silos (four) with pneumatic conveyance – Solids handling systems with weight recorders.
- Dry feeds blender/feed hopper – Solids handling systems with weight recorders and pneumatic or mechanical blending.
- Batch mixer/container filling – Slurry mixing system.
- Vessel vent offgas system – Simple offgas system with HEPA filtration – may include a carbon bed for mercury.
- Container decontamination (moderate complexity) – Robotic? contamination measurement and decontamination system.
- Container shipment/load out station – Hoist and forklift operations.
- Container box disassembly and emplacement at IDF – Forklift and crane operations.

3.1.1.2.2 Accuracy of controls needed

- Sampling/measurements needed to control process – Batch qualification gives composition for grout/quantity of additives. Consequence: Reduced waste loading.
- Modelling needed to control process – Grout process is driven by water content – relatively simple and easy to measure. Consequence: Errors cause grout to either set too slow or not at all, or does not flow into containers, requiring modification of composition.
  - Failure modes for improper operation – Mixture of additives inadequate to form a compliant waste form due to out-of-spec composition or inadequate mixing.

3.1.1.2.3 Commercially available/similar (of a type) to available/bespoke systems – Most unit operations for grout use commercially available systems. Container sealing/closure for contamination control may be only bespoke system. Consequence: Redesign of a component may cause short delays.

3.1.1.2.4 Overall flowsheet integration complexity – (10 unit operations identified. Unit operations are sequential, easily decoupled, few feedback loops.) Consequence: Low throughput. Mitigated by assumed over-capacity design of system, lessons learned from SRS or other sites. The use of an off-site grout production facility can accelerate retrievals; provide flexibility; increase DST headspace by allowing supernatant liquid treatment; reduce SST leakage risk; and reduce cross-site transfer of supernatant liquid.

3.1.1.3. Required facilities/infrastructure (i.e., construction execution risk; system integration; including failure risk of existing infrastructure needed)

- Construction risk is low – Mostly commercially available equipment, experience with saltstone. Small construction site size reduces amount of soil disturbance needed, impact of and on collocated processes.
- Utility usage (electrical, cooling water, steam, etc. is low).
- Integration is simple – Feed line to facility all that is needed except for feeds with LDR organics that require diversion.
- Cross-site supernatant liquid transfer line is not needed to support this alternative.
- Rail line spur.
- Liquid loadout facility.

Consequence: Minimal delays.

3.1.1.4. Required demolition/removal/modification – Not expected to be an issue; no demolition needed. Small size for grout facility makes siting easier. Offsite: Off-site disposal locations may need expansion.

3.1.1.5. Technology Maturity including Test Bed Initiative
[MOE: Completely ready to requiring development to make process work.] – Grout has been produced from Hanford tank waste as part of the Test Bed Initiative. Shipping grouted Hanford waste offsite successfully demonstrated during Test Bed Initiative. Grout in general has been demonstrated at scale; saltstone at SRS (similar process, scale, and waste operations since 1990) and INL, etc. (including containerized grout). Long-term performance predicted by modeling/theory/simulation and followed up with core sampling. Adding iodine getters has not been demonstrated at scale. Shipping of containerized grout has been done (NNSS). Evaporation of alkaline tank waste has been done for decades at Hanford and SRS but measuring effectiveness of removing most LDR organics has not been done at scale. Low-temperature oxidation not demonstrated at scale on Hanford waste, but has been tested at other sites with other organics (e.g., glycolate destruction at SRS for DWPF effluents). Consequence: Continue shipping offsite until onsite is available.

3.1.2. Robustness to known technical risks (ability to recover from things that go wrong in above list; take credit for optional/conditional handling aspects of the alternative but must include in costs also). [MOE: Very robust to very fragile.]

3.1.2.1. Process and equipment robustness – Process and equipment are robust; failure of equipment well understood; grout formulations well understood and can be optimized; iodine getter is not well understood but can be developed.
Failed equipment or plugged lines quickly replaceable. Consequence: Short processing delays. Mitigated by experience at SRS and other facilities.

3.1.2.2. Recovery from unexpectedly poor waste form performance – If future information indicates unexpectedly poor waste form performance, remediating the waste form could be necessary. It is considered plausible to retrieve the waste form with current techniques. Consequence: Retrieve the containerized material or add an additional robust cap (e.g., as a defense-in-depth measure) or barrier or other technology may be an alternative.

3.1.3. Adaptability to a range of waste compositions
[Consider high heavy metals, high non-pertechnetate, ionic strength levels, phosphates, non-RCRA organics, etc.] – Grout formulations can be adapted to accommodate wide range of compositions; if a waste cannot be accommodated by grouting, it will be diverted for vitrification (including if untreatable for LDR organics, possibly for high non-pertechnetate, etc.). Consequence: short processing delays. Mitigated by experience at SRS and other facilities.

3.1.4. Ability to incorporate future advances (include considering different implementability in modular plants vs. big plants)
[MOE: Easily incorporated to impossible.] – Improvements to grout formulations could be accommodated relatively easily (e.g., additional dry feed component). Systems and unit operations are modular and relatively inexpensive. Updates to grout formulation easily incorporated.

Unlikely vendors need to expand capacity but expect that vendors could handle variability in flow rates so expansion unlikely to be needed. Some vendors may need permit changes. Consequence: Minimal cost and short delays. Expect that initial on-site system would be oversized to handle variability in flow rates so expansion unlikely to be needed. Consequence: Minimal cost and short delays. Additional time to begin on-site disposal allows additional development time.

3.2. Likelihood and consequences of failing to complete due to resource constraints

[MOE: No possibility of failure to failure assured.]

3.2.1. Annual average spending
[MOE: Annual average spending requirements against benchmark annual supplemental LAW treatment budget.] – The funding needs for a supplemental LAW grout facility would likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr). Spending includes both 200 East Area plant construction while also paying off-site vendor and transporting waste, but benefit is early start.

3.2.2. Projected peak spending

[MOE: Projected peak spending level (supplemental LAW treatment only) against benchmark annual supplemental LAW treatment budget] – The peak funding needs for a supplemental LAW grout facility would likely be beneath the benchmark funding level for a supplemental LAW treatment facility ($450M/yr). Higher costs overall but could spread costs over one additional year.

3.2.3. Schedule flexibility – Ability to adapt to changes in workload/pace/budget

[MOE: Ability to start and stop construction and operations in response to external factors.] Grout facilities use predominantly commercially available equipment for construction, so stopping/restarting are possible. Grout facilities are typically able to operate below maximum rates by simply stopping operation until feed is available and restarting when feed becomes available. No equipment needs replacement on stop/restart.

3.2.4. Expected work remaining at failure point

[MOE: Failure not likely until end of mission to failure likely prior to start of processing.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.)

Operations, shipping, and disposal are more expensive than expected for containerized grout. Consequence: Operations cease soon after startup, leaving most waste untreated and require need to select alternate solution. Off-site disposal option allows flexibility in the event of on-site disposal issues and off-site immobilization step mitigates on-site facility issues. Mitigated by on-time startup and minimal costs incurred.

3.2.5. Worst plausible case work remaining at failure

[MOE: Failure easily mitigated to allow mission completion to failure cannot be mitigated and mission cannot be finished as intended.] (Note: Assume it fails due to resources; reason is funding shortfall/timing; describe when it fails; MOE is consequence only.) – Construction of the on-site facilities does not start or stops until funding is available. Worst case is to continue off-site grout. Consequence: Costs of off-site disposal and grouting must continue longer than projected. Sufficient funds would likely be available to complete a grout capability by the project need date.

3.3. Likelihood and consequences of failing to complete due to **unavailability of key services and materials**

[MOE: No possibility of materials or services not available to likely that limited resources will impact production (e.g., off-site vendor; special ingredient; sole source provider).]
Highly unlikely. Grout processing is performed in a large number of industrial applications; it is expected that a grout facility would use commercially available equipment and that similar equipment could be procured from other vendors if a vendor for a specific piece of equipment becomes unavailable. Slag and fly ash are typically qualified and sourced from a single supplier; but alternates could be developed, qualified, and readied for deployment to substitute if the need arises. If the vendor is unable to perform the task, another vendor could be selected. Consequence: The process impact would be a delay in processing until an alternative is identified if an ingredient cannot be procured and one has not been preselected. Offsite: Another disposal location must be identified.

Limited use of sampling because the batch qualification process should provide all the information needed to support the grout process; utilization of power, cooling water and other utilities is minimal for the grouting process.

4. Lifecycle Costs

(discounted present value)

Costs must include any optional or conditional operations or processes assumed in performance and performance risk assessments above. All costs are discounted at 3% rate.

Total: $4,127 M

4.1. Capital project costs (including demo/mod of existing infrastructure and R&D)

$1,393 M (includes for commissioning costs)

4.2. Operations costs

$2,734 M

4.3. Shutdown and decommissioning costs

All shutdown and decommissioning costs are assumed at 5% of capital costs and are not included in the total above. The projected costs do not alter the ranking of alternatives.

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Appendix D. Summary of Disposal Site, Transportation, and Off-Site Disposal Considerations

D.1 INTRODUCTION

This appendix provides a summary of Volume II, Appendices G and H, which provide detailed additional information on potential waste disposal sites for treated low-activity waste (LAW) and transportation-related considerations for LAW, respectively. A difference between the information in this appendix and in Volume II, Appendices G and H, is that this appendix focuses on the transportation and cost information related to the four alternatives that were evaluated in detail, as discussed below.

LAW immobilized by the alternatives described in this report will be permanently disposed either on or off the Hanford Site. A combination of on-site and off-site disposal is also plausible. The three disposal facilities discussed in Volume II, Appendix G are identified below and are summarized further:

- **Integrated Disposal Facility (IDF)** (Hanford Site) – A U.S. Department of Energy (DOE) facility that is permitted by the Washington State Department of Ecology (Ecology) for disposal of mixed low-level waste (MLLW) from Hanford Site operations, primarily from wastes currently stored in tanks grouped in 18 separate tank farms. This disposal site is applicable to alternatives Vitrification 1 and FBSR 1A, and to the hybrid alternative Grout 6.
- **Energy*Solutions* Disposal Facility** (Clive, Utah) – This disposal facility is commercially operated by Energy*Solutions* and is licensed by the state of Utah (a U.S. Nuclear Regulatory Commission [NRC] Agreement State) and the U.S. Environmental Protection Agency (EPA) to dispose of low-level waste (LLW) and MLLW. This disposal site is applicable to alternatives Grout 4B and the hybrid Grout 6.
- **Waste Control Specialists (WCS) Waste Disposal Facility** (Andrews, Texas) – This disposal facility is commercially operated by WCS and is licensed by the state of Texas (also an NRC Agreement State). This disposal site is applicable to alternatives Grout 4B and the hybrid Grout 6.

For the two off-site disposal sites, transportation programs will be required to ensure safe and secure transport of two LAW waste forms evaluated in this study from the Hanford Site to the WCS Waste Disposal Facility (Texas) and Energy*Solutions* Clive Disposal Facility (Utah). As noted above, the only LAW treatment waste form considered for off-site disposal is grout; therefore, details on transportation and disposal of the fluidized bed steam reforming (FBSR) waste form at those facilities is not discussed. The analysis does address transporting supplemental liquid LAW to an off-site vendor facility for grouting and subsequent transport to Clive and WCS, and for transporting the liquid supplemental LAW directly to the two disposal facilities for both grouting and disposal. The vitrified and FBSR waste forms evaluated in this study would be disposed of onsite in the IDF. The off-site transportation programs incorporate packaging requirements, transportation routes and schedules, documentation, transportation and disposal costs, specific technical considerations, and qualitative risk evaluation.

D.2 DISPOSAL SITES

D.2.1 Integrated Disposal Facility

The IDF, located in the 200 East Area of the Hanford Site, provides a disposal facility for LLW and MLLW. The Hanford Site is located within the Columbia Plateau between the Cascade Range and the Rocky Mountains. This portion of the plateau is also known as the Columbia Basin, as it is a topographically low area surrounded by mountains on all sides. Cataclysmic ice age flooding inundated the area, depositing sediment that is informally called the Hanford formation. The underlying basalts form a block of rock that is surrounded by active fault zones where stresses are mostly relieved. Therefore, stress relief and ground motion on the Columbia Plateau are relatively small.

The IDF is situated approximately 90 to 100 m (300 to 330 ft) above the water table, with the liner approximately 70 m (230 ft) above groundwater. There is approximately 137 to 167 m (450 to 550 ft) of unconsolidated to semi-consolidated sediments over basalt bedrock underlying the disposal site.

Constructed in 2006, the IDF comprises two expandable disposal cells (Figure D-1). Cell 1 is permitted as a dangerous waste landfill under the *Resource Conservation and Recovery Act of 1976* (RCRA), which allows for disposal of radioactive MLLW (WA 7890008967, "Hanford Facility RCRA Permit"). The dangerous waste component is regulated under *Washington Administrative Code* (WAC) 173-303, "Dangerous Waste Regulations," by Ecology. Cell 2 is limited to radioactive LLW only. An update to the waste analysis plan was included in a permit modification request (Vance, 2021) submitted to Ecology in June 2021 and is under review with Ecology. Upon approval, the permit would, among other things, allow disposal of mixed waste in Cell 2 and allow for disposal of secondary waste from the Waste Treatment and Immobilization Plant (WTP) vitrification activities. The radioactive components of both LLW and MLLW are regulated by DOE under DOE O 435.1, *Radioactive Waste Management*. The disposal cells include a leak detection system to collect leachate (WA 7890008967, "Hanford Facility RCRA Permit").

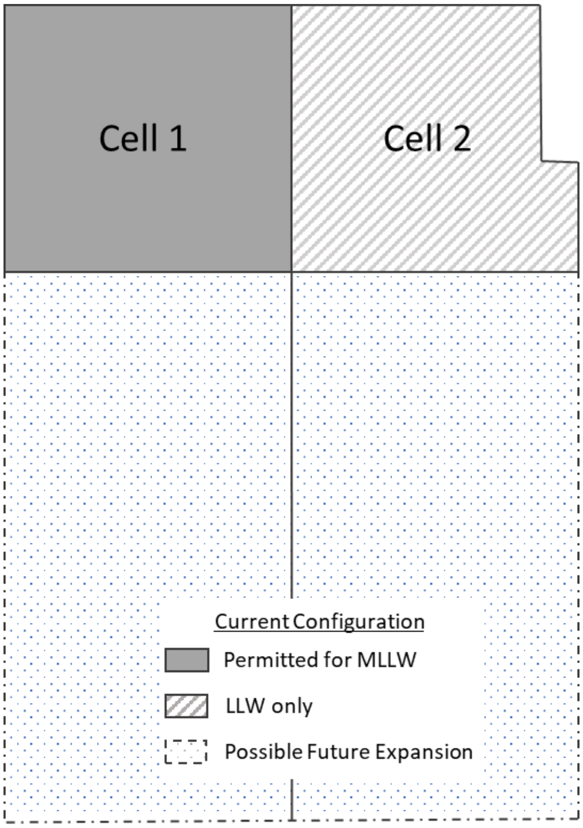


Figure D-1. Integrated Disposal Facility Configuration

Landfill Construction

The IDF liner system includes an operations layer, a leachate collection and removal system (LCRS), a leak detection system (LDS), and a secondary leak detection system (SLDS).

The operations layer, consisting of well-graded granular soil, acts as an insulating layer and protects the underlying liner from damage by equipment and from freezing and desiccation cracking.

Below the operations layer, the LCRS comprises two geotextiles and a gravel layer, followed by a geomembrane liner made of high-density polyethylene and a geosynthetic clay liner that act as moisture barriers. The LCRS is designed so that leachate flows through a perforated pipe above the primary liner into the LCRS collection sump. Below the LCRS is the LDS, which is used to collect any leachate that leaks through the LCRS. The LDS has a similar configuration, as the LCRS (except a composite drainage net) replaces the gravel layer and there is no perforated drainage pipe. The LDS geomembrane liner conveys leachate to the LDS sump for removal. The collected leachate is pumped to two leachate collection tanks until transfer to a treatment, storage, and disposal unit (WA 7890008967).

The IDF liner system also includes an SLDS, which includes an operations layer, drainage gravel, a composite drainage net, and a geomembrane. The SLDS liner is not a regulatory design requirement, but is a redundant leak protection system that collects any leachate that leaks through both the LCRS and LDS. Liquids in the SLDS are removed manually through a portable pump and then transferred to the leachate collection tanks.

Landfill Cover

The final cover design of the IDF has not been completed, but a general conceptual design has been developed. The general design is to cover the IDF with a modified RCRA Subtitle C barrier, which provides a surface barrier for long-term containment, hydrologic protection, and minimizes physical intrusion and recharge. A Subtitle C barrier is the baseline design for a disposal facility containing both dangerous waste (as defined by Washington State regulations) and LLW.

The IDF cover is anticipated to include layers composed of durable material (e.g., topsoil, sand and gravel filter, asphalt base) topped with cover vegetation and a slope (up to 5%) to encourage runoff and minimize the tendency for ponding of rainwater. These layers are intended to divert moisture that may come through the surface barrier away from the trench. The RCRA Subtitle C barrier is to be constructed with a minimum depth of at least 5 m (16.4 ft) to provide shielding from radioactive material and deter intrusion. The cover will include a vegetated surface layer of fine-grained soils to retain moisture, encourage evapotranspiration, and minimize infiltration (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

Key Regulatory Requirements

Disposal in IDF requires a determination that the waste incidental to reprocessing (WIR) requirements of DOE O 435.1 have been met, allowing some tank wastes previously managed as high-level waste (HLW) to be disposed of as LLW. In addition, DOE O 435.1 requirements for near-surface disposal of LLW must be met. The LLW requirements are substantially addressed through a DOE Performance Assessment (PA) that evaluates the long-term impact of near-surface disposal through computer modeling analysis, to provide DOE with a reasonable expectation that LLW and MLLW disposal will meet the radiological performance objectives documented in DOE M 435.1-1, *Radioactive Waste Management Manual*.

Because IDF construction, operations, and closure occur under DOE's regulatory authority under the *Atomic Energy Act of 1954* (AEA), it is not required to meet NRC's LLW classification system at Title 10, *Code of Federal Regulations*, Section 61.55 (10 CFR 61.55), "Waste Classification;" however, as noted below, the waste acceptance criteria for the IDF contains limits for waste to be accepted.

In accordance with the criteria set forth in DOE M 435.1-1, a final WIR evaluation (DOE-ORP-2022-03, *Final Waste Incidental to Reprocessing Evaluation for Vitrified Low Activity Waste and Secondary Waste at the Hanford Site, Washington*) was prepared to address the waste from the Hanford Site underground tanks that will have key radionuclides removed to the extent practical, be stabilized via vitrification to be at Class C levels or less, and meet the IDF waste acceptance criteria.

Performance Assessment

In 1999, the initial PA for the IDF (DOE/RL-97-69, *Hanford Immobilized Low-Activity Tank Waste Performance Assessment*) was approved, followed by an update in 2001 (DOE/ORP-2000-24, *Hanford Immobilized Low-Activity Waste Performance Assessment: 2001 Version*). Additional revisions to the PA were deferred until completion of DOE/EIS-0391, *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (TC&WM EIS), in 2012. This EIS resulted in a Record of Decision (78 FR 75913, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington, Record of Decision") to implement disposal of the following waste types in the IDF:

- LLW and MLLW from tank waste treatment activities generated from the WTP
- On-site non-CERCLA non-tank waste
- Fast Flux Test Facility decommissioning waste
- Effluent Treatment Facility-generated solid secondary waste

- On-site waste management waste.

Based on the Record of Decision, a new PA was prepared to examine the long-term effects associated with the planned waste types. The current PA for the IDF (RPP-RPT-59958), was publicly released in 2019 and includes computer modeling of the near-surface disposal of LLW and MLLW at IDF.

DOE LLW disposal requirements in DOE M 435.1-1 require that a PA "must provide reasonable expectation that the facility will not exceed the performance objectives for a period of 1,000 years following closure of the facility." The 2019 IDF PA included analyses for the required 1,000-year period, but also from 1,000 to 10,000 years, and an extended runout to 500,000 years after closure. The IDF PA has been reviewed and approved by DOE, and an Operating Disposal Authorization Statement has been issued, licensing IDF for disposal of radioactive materials for vitrified primary waste and grouted secondary waste.

Although the most current revision of the IDF PA was completed in 2019, the technical basis supporting the PA is maintained through continued updates that evaluate changes to the PA inputs and assumptions. An annual assessment of these changes is performed to ensure that the conclusions of the PA are still valid.

Overall, groundwater models predict compliance with the 1,000-year performance objectives. Within the 10,000-year period, models predict compliance with performance objectives, with ^{99}Tc and ^{129}I as the primary contributing dose to a representative member of the public. For the atmospheric pathway, the PA shows the IDF meets the performance objectives for the 1,000-year post-closure period.

In addition to assessing pathways, an analysis was performed to calculate the dose equivalent for a future member of the public that intrudes on the IDF. This type of scenario is used to establish radionuclide concentration limits for disposal. In the IDF PA intruder scenario, a hypothetical driller of groundwater uncovers waste disposed of in the IDF. Both acute and chronic exposures were considered and evaluated for up to 1,000 years after closure of the IDF, following at least 100 years of institutional controls. Based on these analyses, the three chronic exposures scenarios evaluated (rural pasture farmer, suburban garden resident, and commercial farm worker) were below the 100 mrem chronic dose performance measure and the acute well driller scenario dose was below the 500 mrem acute dose performance measure.

Waste Acceptance

A waste acceptance criteria document for the IDF has been finalized and defines the acceptance criteria for LLW and MLLW, and the requirements for complying with the IDF Disposal Authorization Statement (Gilbertson, 2021) per DOE M 435.1-1 and RCRA permit (Vance, 2020). The waste acceptance criteria prohibit HLW from acceptance and disposal at IDF.

The IDF is permitted by Washington State as Operating Unit Group 11 under Revision 8c of the Hanford Facility RCRA Permit. Currently, the IDF permit authorizes disposal in only one cell (Cell 1). Cell 1 is permitted to dispose of MLLW, limited to immobilized LAW from WTP, immobilized LAW from the demonstration bulk vitrification system, and IDF operational wastes (WA 7890008967).

Currently, waste acceptance criteria for the IDF includes the following requirements:

- Wastes must be compliant with RCRA Land Disposal Restrictions (LDR) (40 CFR 268, "Land Disposal Restrictions").
- Transuranic wastes are prohibited.
- Free liquids are prohibited, unless one of the provisions in the following section of WAC 173-303-140(4)(b)(ii) can be met.
- Pre-waste acceptance is required; waste pedigree needs to be verified by IDF personnel.
- Comply with the maximum void space requirements for containers (i.e., must be >90% full).

Dangerous waste performance information has been included in the DOE-mandated PA required by DOE M 435.1-1 (RPP-RPT-59958). This PA is required for analysis of radioactive constituents, although an assessment of dangerous waste was included to meet the IDF RCRA permit condition. One aspect of the permit is creation and maintenance of a Risk Budget Tool to model future impacts of the planned IDF waste forms to the vadose zone and groundwater, such that if modeling results are within 75% of a performance standard, the permit requires DOE and Ecology to discuss mitigation measures or modified waste acceptance criteria (IDF RCRA permit condition III.11.I.5.a.ii). Additional waste analysis and acceptance permit conditions may be included upon approval of the permit modification request. Grouted waste forms from supplemental LAW treatment are not included in the list of waste streams currently approved for disposal in the IDF RCRA permit or the DOE M 435.1-1 Disposal Authorization Statement (Gilbertson, 2021).

Waste Capacity

Plans for the IDF include future construction to expand the disposal cells to a length of 501 m (1,645 ft) and width of 410 m (1,345 ft) at ground level, with a depth of 12.8 m (42 ft). The IDF PA assumes that waste loading will comprise 40% of the total available IDF capacity, with the remainder consisting of backfill. This results in a maximum waste disposal capacity of 900,000 m^3 (1,200,000 yd^3) (RPP-RPT-59958).

System Plan (ORP-11242, *River Protection Project System Plan* [Rev. 9]) waste disposal volumes were estimated for several scenarios that evaluated different volumes split between first LAW and supplemental LAW capacities. Volumes of both vitrified waste and grout for the supplemental LAW volume were presented and used to compare the volumes disposed of onsite in the IDF in the various alternatives (Table D-1). The baseline case, Scenario 1, in the System Plan considers a split of 59% to first LAW and 41% to supplemental LAW. The presented values are based on this scenario, where the IDF capacity is not exceeded in any cases. Note that one scenario (Scenario 3) presented in the System Plan would exceed the IDF capacity, where over 72% of the treated LAW feed is directed to supplemental treatment.

Based on this data, all supplemental LAW treatment technologies would produce waste within the waste disposal capacity of IDF (Table D-1).

Table D-1. Estimated Disposal Volumes to the Integrated Disposal Facility

Waste Type	System Plan[a]	LAW Supplemental Treatment Alternatives[b]		
	Scenario 1 m^3 (yd^3)	Grout Onsite m^3 (yd^3)	Grout Offsite m^3 (yd^3)	FBSR m^3 (yd^3)
Immobilized LAW	190,074 (250,097)[c,d]	112,143 (147,557)[e]	112,143 (147,557)[e]	112,143 (147,557)[e]
Grout (primary waste)	0	304,000 (400,000)[f]	0	0
FBSR	0	0	0	202,667 (266,667)[g]
Secondary waste	41,397 (54,469)	24,424 (32,137)	24,424 (32,137)	28,072 (36,936)[h]
Total | % IDF capacity	**231,471 (304,567) | 26%**	**440,567 (579,693) | 49%**	**136,567 (179,693) | 15%**	**342,882 (451,161) | 38%**

[a] ORP-11242, 2020, *River Protection Project System Plan*, Rev. 9, U.S. Department of Energy, Office of River Protection, Richland, Washington.

[b] Secondary waste volumes calculated based on the assumed ratio of secondary waste projected for the full immobilized LAW inventory in the IDF PA, Table 3-26 (0.218 ratio) (RPP-RPT-59958, *Performance Assessment for the Integrated Disposal Facility, Hanford Site, Washington*).

[c] Taken from Scenario 1 of ORP-11242 [Rev. 9], Table ES-4, assumes 5.51 MT of immobilized LAW per container and a density of 2.58 kg/L (MT/m^3) for the LAW glass.

[d] The LAW supplemental treatment alternative Vitrification 1 would result in equivalent waste disposal volumes as the IDF PA Baseline Case.

[e] Based on the amount of WTP LAW glass, assuming 41% of volume is attributed to supplemental LAW (assumed in Scenario 1 of System Plan [Rev. 9]).

[f] Taken from Scenario 1 of ORP-11242 [Rev. 9], Table ES-4.

Table D-1. Estimated Disposal Volumes to the Integrated Disposal Facility

Waste Type	System Plan[a]	LAW Supplemental Treatment Alternatives[b]		
	Scenario 1 m^3 (yd^3)	Grout Onsite m^3 (yd^3)	Grout Offsite m^3 (yd^3)	FBSR m^3 (yd^3)

[g] Calculated based on the grout volume for supplemental LAW from ORP-11242 [Rev. 9], Table ES-4, and assumes the volume multiplier of waste to grout as 1.8, and of waste to FBSR product as 1.2. (Note that the liquid-to-solid volumetric ratio was conservatively assumed to be 1.2 in transport and disposal calculations related to FBSR. The larger ratio results in a larger FBSR waste volume. The FBSR volumetric ratio assumed in all other analyses discussed in this report was 1.0.)

[h] FBSR assumes a ratio of 0.018 units of secondary waste per unit of primary waste generated (RPP-RPT-63580, *Calculating the Non-Monetary Impact of Operating a Fluidized Bed Steam Reforming Facility*) and added to volume of secondary waste from vitrification.

FBSR = fluidized bed steam reforming.
IDF = Integrated Disposal Facility.
LAW = low-activity waste.
PA = performance assessment.
WTP = Waste Treatment and Immobilization Plant.

D.2.2 Energy*Solutions* Disposal Facility (Clive, Utah)

Energy*Solutions* operates a low-level radioactive waste (LLRW) disposal facility west of the Cedar Mountains in Clive, Utah. Clive is located along Interstate 80, approximately 4.8 km (3 mi) south of the highway in Tooele County. The facility is approximately 80.5 km (50 mi) east of Wendover, Utah, and approximately 128.7 km (80 mi) west of Salt Lake City, Utah. The natural topography slopes slightly toward the southwest with approximately 3 m (10 ft) of relief from the northeast corner of the section to the southwest corner of the section. An aerial view of the facility is shown in Figure D-2.

Figure D-2. Aerial View of the Clive Facility

The initial selection of the site location dates back to the late 1970s when DOE and the state of Utah began the cleanup of an abandoned uranium mill site. The Vitro mill site, located in central Salt Lake City, was one of the first sites cleaned up under the DOE Uranium Mill Tailings Remediation Action (UMTRA) Program. DOE investigated 29 sites to identify the safest permanent disposal site for these materials. After 8 years of characterization and evaluation of several sites, DOE selected the Clive site located in Utah’s West Desert. The site’s remote location, low precipitation, general absence of groundwater, and low-permeability clay soils were some of the attractive qualities of the area.

From 1984 to 1988, the Vitro tailings were relocated to Clive and placed in an above-ground disposal cell. Since acquiring land adjacent to the Vitro disposal embankment and obtaining a disposal license, the vision of the Energy*Solutions* Clive facility has been to provide a private disposal option for material from government and commercial environmental cleanups and generators of radioactive waste in separate disposal embankments similar to those used for DOE’s Vitro project.

The Clive facility has received waste from cleanup activities carried out across the country, including projects by the EPA, DOE, U.S. Department of Defense (DoD), utilities, and other commercial entities. The initial disposal license was for naturally occurring radioactive material (NORM). Since 1988, the Energy*Solutions* radioactive material license has been amended several times, expanding the types of radioactive materials to include Class A LLRW, in addition to NORM.

The facility is 2.6 km^2 (1 mi^2) in size. The DOE-owned Vitro property occupies approximately 100 ac of the facility. Figure D-3 shows the disposal cells and major man-made and topographic features at the facility. The facility is accessed by both road and rail transportation.

Energy*Solutions* began waste disposal activities at the facility in 1988. At present, waste is placed in one of three disposal embankments: Class A West (CAW), mixed waste, or 11e.(2). A fourth embankment, the low-activity radioactive waste (LARW) embankment, located between the mixed waste and 11e.(2) embankments, was closed in October 2005. On November 26, 2012, the Utah Division of Radiation Control approved an amendment to the Energy*Solutions* radioactive material license UT 2300249, "Radioactive Material License Number UT 2300249," to combine the Class A and Class A North embankments into the CAW embankment.

The CAW embankment contains the large component disposal area and the Containerized Waste Facility. In the north-central part of the facility, DOE has disposed of the Vitro uranium mill tailings. This area is owned and monitored by the DOE.

Source: Figure 1 of Energy*Solutions*, 2015, *Bulk Waste Disposal and Treatment Facilities Waste Acceptance Criteria*, Rev. 10, Energy*Solutions*, Salt Lake City, Utah.

Figure D-3. Clive Facility Disposal Cells and Main Features

Waste disposal cells at the site are permanent, clay-lined cells with composite clay and rock cap designed to perform for a minimum of 500 years.

Hydrogeology and Climate

The soil deposits at the facility are the Quaternary-age lacustrine lake bed deposits associated with the former Lake Bonneville. These surficial lacustrine deposits generally comprise low-permeability silty clay.

Beneath the facility, the sediments consist predominantly of interbedded silt, sand, and clay with occasional gravel lenses. The depth of the valley fill beneath the facility is unknown; estimates range from 250 to 3,000 ft below ground surface.

The climate at the facility location is semi-arid with an average precipitation of 8.43 in./year and average pan evaporation of 53.3 in./year based on on-site data collected from 1993 to 2018.

The regional groundwater flow direction is toward the Great Salt Lake to the east-northeast. Groundwater recharge to alluvium-filled valleys in the Basin and Range Province occurs primarily through the alluvial fan deposits along the flanks of the adjoining mountains. Because of the low precipitation and high evapotranspiration, direct infiltration of water into shallow aquifers in the valley floors is negligible.

Both a shallow unconfined aquifer and a deep confined aquifer lie below the facility. Isotopic studies conducted to characterize groundwater recharge sources, groundwater age, and groundwater geochemical evolution indicated that the ionic composition of groundwater at the facility was consistent with very slow horizontal flow rates. The groundwater in both aquifers is extremely saline. The salinity of the water is high because of dissolution of evaporite deposits and concentration of salts due to evapotranspiration. Groundwater beneath the facility is classified as a Class IV saline groundwater under the state of Utah Groundwater Quality Protection Regulations standards for total dissolved solids (exceeding 10,000 mg/L) (*Utah Administrative Code* [UAC] R317-6-3, “Ground Water Classes”). Naturally occurring concentrations of many dissolved constituents (e.g., arsenic, selenium, thallium, radium, and uranium) exceed EPA and Utah State drinking water standards (Mayo and Associates, 1999; Bingham Environmental, 1996; Energy*Solutions*, 2014).

Disposal Facility Design

The design and operation of the Energy*Solutions* disposal site provides a long-term disposal solution with a minimal need for active maintenance after closure. Energy*Solutions* uses an above-ground engineered disposal cell. The design of these cells is patterned after DOE and EPA specifications for the Vitro disposal embankment.

The design of the CAW cell is similar to the design of the existing Class A cell, with a larger footprint. The CAW disposal cell occupies approximately 133 ac. The cell is excavated into the native silty clay soil with waste placed above a layer of compacted clayey soils and covered with a layered engineered cover constructed of natural (no man-made) materials. The cover design is engineered to reduce infiltration, prevent erosion, and protect from radionuclide exposure. The landfill design includes both a low-angled top slope and a steeper side slope section of the cover. The layers of the CAW top slope cover consist of the following from bottom to top:

- **Liner**. The cell will be lined with a 0.61 m (2-ft) thick layer of compacted clayey native soil (Unit 4).
- **Waste**. The waste layer will not exceed a final thickness of 23 m (75.3 ft) above the top of the clay bottom liner. The height of waste at the shoulder of the top slope (the contact between the top slope and side slope) will be approximately 11.4 m (37.6 ft).
- **Radon barrier**. The top slope cover design contains an upper radon barrier consisting of 0.3 m (12 in.) of compacted clay with a maximum hydraulic conductivity of 5×10^{-8} cm/sec and a lower radon barrier consisting of 0.3 m (12 in.) of compacted clay with a hydraulic conductivity of 1×10^{-6} cm/sec.
- **Filter zone (lower)**. The 0.15 m (6 in.) of Type B filter material will be placed above the radon barrier in the top slope cover.
- **Sacrificial soil (frost protection layer)**. A 0.3 m (12-in.) layer consisting of a mixture of silty sand and gravel will be placed above the lower filter zone to protect the lower layers of the cover from freeze/thaw effects.
- **Filter zone (upper)**. The 0.15 m (6 in.) of Type A filter material will be placed above the sacrificial soil in the top slope cover. The Type A material-size gradation corresponds to a poorly sorted mixture of coarse sand to coarse gravel and cobble.
- **Rip rap cobbles**. Approximately 0.45 m (18 in.) of Type B rip rap will be placed on the top slopes, above the upper (Type A) filter zone.

The design for the side slope is similar to the top slope, except for the thickness of the waste layer and the material used in the rip rap layer.

- **Waste**. The thickness of waste will range from zero at the edge of the cell to 11.4 m (37.6 ft) at the shoulder, for an average waste height of 5.7 m (18.8 ft) [(0+37.6)/2)].
- **Rip rap cobbles**. Approximately 0.45 m (18 in.) of Type A rip rap will be placed on the side slopes above the Type A filter zone.

Key Regulatory Requirements

The applicable federal agency that regulates disposal of LLRW at the Clive facility is the NRC. The regulations (10 CFR 61, and Utah regulation R313-25-9, "Technical Analyses") indicate the need to evaluate performance with respect to members of the public and inadvertent human intruders.

Energy*Solutions* is permitted by the state of Utah to receive Class A LLW under UAC R313-25, "License Requirements for Land Disposal of Radioactive Waste." The wastes that are received must be classified in accordance with the UAC R313-15-1009, "Classification and Characteristics of Low-Level Radioactive Waste." The classification requirements in UAC R313-15-1009 reflect those outlined in the NRC's waste classification system, 10 CFR 61.55, which divides LLW into classes for disposal – with Class A LLW being the least hazardous and greater-than Class C (GTCC) LLW being the most hazardous. The Clive facility is licensed for disposal of Class A LLW and MLLW and bulk Class A LLW and MLLW in reusable packages with dose rates of <100 mrem/hour at 30 cm (~1 ft).

A determination of the Class of the waste is based upon a comparison against limits in two tables, one for short-lived radionuclides and one for long-lived radionuclides, extracted from 10 CFR 61.55. A detailed projection of waste classes is provided in Section H.6 of Volume II, Appendix H. Calculated results in that appendix show that the percentage of expected LAW from supplemental treatment in a grouted waste form that would be Class A waste range from 83 to 93%, depending on feed vector characteristics and whether a Hanford System Plan representative feed (Scenario SP9 1B) is used or an "Early Start" feed is used (ORP-11242, Rev. 9). The feed vectors represent monthly average concentrations of 46 radionuclides for each month of waste generation. The SP9 1B feed vector is not relevant for purposes of determining classes of waste for the two off-site alternatives analyzed in detail, Grout 4B and Grout 6, as they assume an Early Start feed vector. For alternatives Grout 4B and Grout 6, the percentage of waste form that would be Class A is at the low end of the range above. This is because the concentrations of long-lived radionuclides are higher during this time.

Subpart C of 10 CFR 61 specifies the performance objectives for the near-surface LLW disposal facilities – protection of general population and inadvertent intruders. The near-surface disposal is defined as disposal in or within the upper 30 m (100 ft) of the earth's surface (10 CFR 61.2).

In addition, groundwater protection levels (GWPL) must be adhered to, as outlined in the site's Ground Water Quality Discharge Permit (UWQB, 2010). The GWPLs are numerical standards that are set by Utah Department of Environmental Quality (UDEQ) in the groundwater quality discharge permit (UWQB, 2009). Groundwater in the vicinity of the site is defined as Class IV, saline groundwater (UWQB, 2009), and GWPLs for existing wells were determined by UDEQ according to administrative rules for Class IV saline aquifers. GWPLs were set at the greater of either the Ground Water Quality Standard (GWQS) or the upper boundary of the background concentration.

Waste Acceptance Criteria

The type, form, and quantity of LLRW, NORM, 11e.(2) byproduct material, and mixed waste that can be treated and disposed of at the Clive facility is defined in licenses and permits. The licenses issued to Energy*Solutions* by the Utah Division of Waste Management and Radiation Control applicable to the LLRW and mixed waste are:

- An Agreement State radioactive material license (UT 2300249). This license authorizes Energy*Solutions* to receive Class A LLRW, NORM, and naturally occurring and accelerator-produced radioactive material (NARM) waste.
- A state-issued Part B Permit (EPA ID Number UTD982598898) to treat and dispose of hazardous waste that is also contaminated with LLRW, NORM, or NARM wastes (mixed waste).
- An Agreement State radioactive material license (UT 2300478) for 11e.(2) byproduct material (as defined by the AEA).

In addition to waste acceptance criteria, as low as reasonably achievable (ALARA) criteria are applied to minimize worker exposures. The ALARA criteria are not a license condition but are used as the primary distinction between waste that is acceptable for direct disposal at the Bulk Waste Facility and Containerized Waste Facility. The ALARA criteria define allowable external contact dose rates and loose surface contamination limits for waste managed at the Bulk Waste Facility.

The disposal volume available at Clive is 2,293,665 m^3 (3 million yd^3). Consequently, disposing of all Class A Hanford LAW from supplemental treatment at Clive will take from 8 to 15% of the available disposal volume. Clive does not have a limit on the total activity.

Disposal Performance Evaluation

There are two disposal performance evaluations: (1) Class A West Disposal Cell and (2) a proposed Depleted Uranium Cell. The performance evaluation specifies the dose limits to the general population due to the exposure to the radioactive materials released in groundwater, surface water, air, soil, plants, or animals. Clive is a remote and environmentally inhospitable area for human habitation. Human activity at Clive has historically been very limited, due largely to the lack of potable water or even water suitable for irrigation. None of the exposure pathways at the site are viable as explained below. However, the groundwater pathway was analyzed in great detail to provide evidence that GWPLs in the compliance monitoring well are below the limits outlined in the site’s Ground Water Quality Discharge Permit (UWQB, 2010).

For the Class A West Disposal Cell, the performance evaluation determined the following conclusions for the different pathways and the protection of individuals from inadvertent intrusion. Additional details on the performance evaluation, including a more in-depth discussion of the groundwater analysis, are included in Volume II, Appendix G.

- **Air pathway**: The evaluation determined that radon releases will be negligible because the cover design includes a clay radon barrier designed to limit the surface radon flux to less than 20 pCi/m^2/sec, resulting in potential radon exposures well within limits.
- **Soil pathway**: The soil pathway entails the exposure of the public to contaminated soil from the facility. Both the location of the facility and closure contribute to low exposures as no contaminated soil material is expected to rise to the ground surface or otherwise be removed from the disposal cell.
- **Surface water pathway**: Due mainly to the natural site characteristics, no radioactive releases are expected through the surface water pathway. The annual precipitation is low and evaporation is high. No permanent surface water bodies are on the site.

- **Plant pathway**: Exposures via the plant uptake pathway are not expected. Insufficient water exists at the site to produce food crops. In addition, saline soils present at the site limit the number and type of plant species that can tolerate such conditions.
- **Burrowing animal pathway**: The design of the facility, including the riprap erosion barrier and the clay radon barrier, is expected to preclude burrowing animals from reaching the waste layers.
- **Groundwater pathway**: The groundwater protection criteria are based on an annual dose of 4 mrem to an individual drinking groundwater. The primary site characteristics prevent public exposures via the groundwater pathway due to very poor groundwater quality at the site, low population density, and relatively slow groundwater flow velocities. No domestic water use occurs within 10 km of the facility. Even though the groundwater is not potable, potential doses to the public from groundwater were calculated and met all applicable limits.
- **Inadvertent intruder**: Intruder protection is promoted by the location and design of the disposal facility. The embankment cover system provides the long-term barrier to inadvertent intrusion, with 1.1 m (3.5) ft of rock layers, 0.61 m (2 ft) of clay, and 0.3 m (1 ft) of noncontaminated native soil as a “temporary cover” above the waste. Further, limiting the waste to Class A has been determined to protect inadvertent intruders.

A separate performance assessment has been performed for the Proposed Depleted Uranium Cell. This analysis is documented in Neptune (2021). The PA is probabilistic and goes beyond the 500 years because depleted uranium reaches peak activity at 2.1 Myr. Even though this analysis was done for a different inventory than the one that will be disposed of at the CAW disposal cell, the analysis provides additional confidence in the performance of the Clive facility.

Other Considerations

The following other considerations are summarized below and discussed in more detail in Volume II, Appendix G:

- **Operating experience**: Energy*Solutions* has over 34 years of experience operating the Clive facility. The NORM waste disposal operations at the Clive facility began in 1988. LLRW disposal operations began in 1991. Mixed waste disposal operations have been conducted since 1992. The Clive facility has received waste from cleanup activities carried out across the country, including projects by the EPA, DOE, DoD, utilities, and other commercial entities. Energy*Solutions* received, treated, and disposed of over 1.5 Mgal of waste shipped in International Organization for Standardization tankers from the DOE Rocky Flats closure project. Energy*Solutions* has disposed of more than 2.4 million m^3 (85 million ft^3) of waste from DOE sites over the last 25 years.
- **Compliance monitoring wells**: A compliance monitoring well network was developed for the CAW embankment that includes 27 wells. The monitoring well network is designed to verify regulatory compliance with the state of Utah GWPLs and to provide early warning of potential releases. A well spacing analysis was performed to provide reasonable assurance that releases from the CAW embankment can and will be detected. The modeling was performed using ^{129}I and ^{99}Tc as the surrogate contaminants. These radionuclides were selected because of their potential presence in CAW embankment Class A waste, their conservative transport characteristics (i.e., relatively mobile), and because of their long half-lives relative to the modeled time period of 500 years.
- **Financial assurance**: Funds for the closure, remediation, and long-term surveillance of the Clive facility are maintained in trust for the benefit of the state of Utah. Furthermore, the state of Utah has established a Perpetual Care Fund with a target initial minimum balance of $100 million at the conclusion of the post-closure monitoring period (i.e., year 101 after site closure).

The Perpetual Care Fund is funded by an annual payment, and earnings are accrued to the fund cash balance. In addition to the estimated costs for decommissioning the Clive facility, the financial surety also covers estimated costs of long-term surveillance of the site, including sampling of groundwater monitoring wells, site inspections and repairs, and other miscellaneous costs.

D.2.3 Waste Control Specialists, LLC Waste Disposal Facility (Andrews, Texas)

WCS is a treatment, storage, and disposal company dealing in radioactive, hazardous, and mixed wastes. Their primary facilities are located on 1,338 ac (540 ha) of land that is 35 mi (56 km) west of Andrews, Texas, and 5 mi (8 km) east of Eunice, New Mexico.

Transportation and Disposal

WCS treatment capabilities include dewatering, stabilization, and repackaging. Their transportation capabilities include ownership of three Type B shipping casks and two Type A shipping containers. WCS has three separate disposal facilities for radioactive wastes, including (1) a facility for disposal of commercial radioactive wastes from the Texas Low-Level Radioactive Waste Disposal Compact, and radioactive wastes imported from 36 other states into the Texas Compact; (2) a facility for disposal of 11e(2) byproduct material; and (3) the Federal Waste Disposal Facility (FWF).

Figure D-4 is an aerial view of the disposal facilities for radioactive wastes at WCS. The remainder of this subsection focuses exclusively on the FWF, which was designed, licensed, and constructed for federal waste disposal, including all wastes from DOE.

WCS is equipped to receive wastes by truck and by rail. For rail, a receiving building straddles the railhead and a WCS-owned locomotive brings wastes onsite from nearby Eunice, New Mexico.

Figure D-4. Clive Waste Disposal Facility

The area surrounding the WCS facilities is sparsely populated and (on average) receives less than 400 mm (16 in.) of rainfall per year. Based on an extensive site investigation program, including over 500 wells and core samples, the geology and hydrology of the WCS site is well understood.

Hydrogeology

The WCS facilities are located over a geologic feature referred to as the “buried red ridge”. This buried red ridge is part of another geologic layer that consists of a series of fluvial and lacustrine mudstones, siltstones, sandstones, and silty dolomite deposits that are over 1,000 ft thick beneath the WCS site. The buried red ridge is encountered at depths ranging from about 8 to 80 ft beneath the WCS facilities.

An Ogallala Formation exists to the northeast of the site and extends above the buried red ridge, it is not water bearing in the WCS area. The site is completely isolated from the part of Ogallala formation that is saturated to the north and east of the buried red ridge and from the regional Ogallala Formation in the Southern High Plains. The WCS facilities are not located over a drinking water aquifer or adjacent to any underground drinking water supply.

In the Dockum Group beneath the WCS facilities, there are transmissive zones in the sandstones/ siltstones. The uppermost, laterally-continuous and continuously-saturated transmissive zone is a 10- to 35-ft thick sandstone/siltstone at a depth of about 225 ft. This unit, referred to as the 225-ft zone, has a very low permeability of approximately 10^{-8} cm/sec. WCS has monitoring wells screened in the 225-ft zone in all three landfill areas. Because of the low transmissivity and salinity, the 225-ft zone is not classified as a drinking water aquifer. The groundwater pathway was excluded from the site performance assessment.

Disposal Facility Design

Wastes are emplaced ~8 to 37 m (25 to 120 ft) below the land surface in the FWF disposal cell that includes a 7-ft (2 m) thick multi-barrier liner. When constructed, the multi-barrier cap over the cell will be a minimum of 25 ft (~8 m) thick and will be completed at-grade. Higher-activity Class B and C LLW and MLLW are disposed of in modular concrete canisters (MCC) inside the disposal cell. The MCCs are 150 mm (6-in) thick steel-reinforced concrete containers. The natural site characteristics and barriers (e.g., no drinking water aquifer and thick red clay beds) and the engineered barriers (e.g., 2-m thick multi-barrier liner and MCCs) work together to give WCS one of the most robust multi-barrier designs of any Agreement State-licensed LLW disposal facility in the United States.

WCS uses two standard types of MCC: (1) cylindrical: 1.8 m (6 ft) and (2) rectangular: 2.9 m long × 2.3 m wide × 2.8 m high (9 ft-6 in. long × 7 ft-8 in. wide × 9 ft-2 in. high) (internal). Typically, Class B and C LLW, inside a U.S. Department of Transportation (DOT) shipping container, is placed in an MCC, any void space is grouted and the concrete lid is placed on top. A waste that is disposed of in an MCC is categorized by WCS as a *containerized waste*. In contrast, *bulk wastes* may be shipped in reusable DOT shipping containers, the wastes are not disposed of in the DOT shipping container and the waste is not placed in an MCC. Bulk waste is acceptable for disposal in the FWF, if the waste is Class A and has a dose rate of <100 mrem at 30 cm (~1 ft). Bulk waste is sometimes disposed of in an MCC (e.g., if the dose rate of the bulk waste is >100 mrem at 30 cm [~1 ft]). Figure D-5 shows the wastes being loaded into rectangular MCCs inside a disposal cell with components of the multi-barrier liner visible in the background.

Figure D-5. Wastes Being Loaded into Modular Concrete Canisters at the Waste Control Specialists Disposal Cell

As noted in Section D.1, this study assumes that the waste forms will be shipped and disposed of using 8.4-m^3 “soft-side” shipping containers. If the waste is determined to require containerization, as noted above, two soft-side containers with a capacity of 8.4 m^3 each (11 yd^3) each will fit in a standard rectangular MCC (allowing ~ 50 mm (2 in.) extra on all four sides and 50 mm (2 in.) extra on top).

Key Regulatory Requirements

Texas is an NRC Agreement State, and the Texas Commission on Environmental Quality (TCEQ) is responsible for licensing and inspecting the WCS radioactive and mixed waste disposal facilities. For licensing the FWF, TCEQ used their state regulations that are equivalent to the 10 CFR 61 licensing requirements. After a detailed multi-year licensing process in 2009, TCEQ issued a Radioactive Materials License to WCS to dispose of LLW (TCEQ, 2009).

The following are key FWF regulatory considerations:

- FWF is licensed to accept Class A, B, and C LLW and Class A, B, and C MLLW for disposal.
- Before disposal, all waste must meet LDR requirements in 40 CFR 268 (or state equivalent LDR requirements).
- The FWF is licensed for up to ~736,000 m^3 (26,000,000 ft^3) and 5,600,000 total curies of wastes. The FWF is designed to be built in 11 phases. Only the first of the 11 phases has been completed.

The term of the current license is through September 2024, with provision for 10-year renewals thereafter. The state of Texas takes ownership of LLW disposed of in the Compact Disposal Facility; DOE has signed an agreement to take ownership of the FWF after its closure. In post-closure, DOE will be responsible for the waste forms disposed of in the FWF.

In addition to the license issued by the TCEQ, WCS maintains other permits and licenses, which are listed on their website (WCS, 2022).

Waste Acceptance Criteria

The waste acceptance criteria for the FWF are included as an amendment to the TCEQ license for the FWF; these criteria are detailed in the WCS *Federal Waste Disposal Facility (FWF) Generator Handbook* (WCS, 2015).

The waste acceptance criteria for the FWF include limits on free liquids (<1% of the volume of containerized waste), maximum void space limits, transportation requirements, and prohibited waste types. Prohibited wastes include high-level radioactive waste; waste capable of generating toxic gases (excluding radioactive gases); and waste readily capable of detonation, of explosive decomposition, reaction at normal pressures and temperatures, or of explosive reaction with water.

Some of the general packaging requirements are:

- Each container can only contain one approved profiled (characterized) waste stream
- Packages should weigh 10,000 lb (4,545 kg) or less, unless special arrangements have been made
- All containers transported on public roads to WCS are required to meet the applicable DOT regulations
- Except for bulk wastes and large components, waste packages must fit in an MCC.

The wastes disposed of at WCS must comply with the LDRs detailed in 40 CFR 268. The FWF is licensed for disposal of Class A, Class B, and Class C (as defined in 30 TAC 336.362, “Appendix E. Classification and Characteristics of Low-Level Radioactive Waste”) LLW and MLLW, and bulk Class A LLW and MLLW in reusable packages with dose rates <100 mrem/hr at 30 cm (~1 in.). The percentages of waste that would be Class A, Class B, or Class C are expected to be the same, as discussed in Section D.2.2, for Clive (Energy*Solutions*). In all grout cases, the Class B and C waste forms are produced only during the first 7 years of operations for alternatives using the Hanford SP9 1B supplemental LAW characteristics or during the first 18 years of operations (Early Start).

Disposal Performance Evaluation

The WCS disposal PA (WCS, 2011) examines site features such as geology, surface water and groundwater, potential future weather changes, residential and intrusion scenarios, and possible future uses of the land. The WCS PA meets all state of Texas requirements during the performance period of 10,000 years after site closure.

When considering transport in the porous-medium water phase, inventory radionuclides are assumed to be uniformly distributed and available for leaching by a conservative partition coefficient (K_d) exchange leaching model. This leaching model conservatively assumes that all the radionuclides are available for contact with water and migration. No credit is taken for waste containers, concrete canisters, or improved waste forms such as activated metals or solidified or encapsulated wastes. The entire radionuclide inventory is immediately available for release and transport (WCS, 2007, Appendix 8.0-6).

Radionuclide pathways analyzed in the PA include the following:

- **Surface water pathway** – The surface water pathway was determined to be irrelevant for contaminant release due to a number of factors, including the semi-arid nature of the location where the loss of water by evapotranspiration exceeds precipitation, the absence of streams on or near the site, and the good drainage of site soils.
- **Air pathway** – The air pathway for the WCS Site Model is largely driven by gas emanation through the finished cover. The air pathway is the main risk driver for longer lived, highly mobile radionuclides such as ^{129}I or ^{14}C.
- **Groundwater pathway** – Although there are no potable water sources in the area near the WCS facility and very low vertical velocity beneath the WCS site, the groundwater pathway was analyzed in detail and potential impacts were quantified. The conclusion of these analyses was that there is no realistic groundwater pathway at WCS (WCS, 2011).
- **Other analyzed exposure pathways** – Intruder analyses were also considered, including an intruder driller and an intruder resident. Additionally, an adjacent resident was also evaluated, with the gaseous diffusion and corresponding inhalation dose determined to be the dominant exposure pathway.

Other Considerations

Other considerations include:

- **Waste ownership** – Upon receipt, Texas Compact LLW waste ownership is transferred to the state of Texas and federal LLW is transferred to DOE after post-closure of the FWF.
- **Retrievability** – The Class B and C waste will be disposed of in MCCs. MCC placement allows for waste retrievability via global positioning system technology.
- **Monitoring well network** – Over 400 monitoring wells are measured quarterly, many of which are dry. Approximately 150 monitoring wells are laboratory sampled semi-annually if there is enough water.

D.3 TRANSPORTATION

This section primarily focuses on transportation to the off-site disposal facilities: Energy*Solutions* in Clive, Utah, and WCS near Andrews, Texas. Transportation of LAW to the IDF would follow the same essential requirements as the vitrified waste from the WTP LAW facility. For disposal at IDF, waste forms considered in the analysis included vitrified waste, grouted waste, and a FBSR waste form. For off-site disposal, only waste forms from grouting or FBSR alternatives were considered. This is because current planning, permits, and existing and planned infrastructure support disposal of a vitrified waste form in the IDF and there was not perceived to be any advantage to disposing this waste form offsite.

Per DOE O 460.1D, *Hazardous Materials Packaging and Transportation Safety*, DOE has broad authority under the AEA, as amended, to regulate activities involving radioactive materials that are undertaken by the DOE or on its behalf, including the transportation of radioactive materials. In most cases that do not involve national security or other critical interests, DOE uses commercial carriers that undertake its shipments subject to regulation by DOT and NRC as appropriate. However, DOE exercises its AEA authority to regulate certain DOE shipments, including shipments by government employees and on-site transfers. In all cases, DOE's packaging and transportation activities must be conducted in a manner that achieves an equivalent level of safety to that required by DOT and NRC for comparable commercial shipments. Requirements are specified under DOE's directive system through DOE Orders and Manuals:

- DOE O 460.1D establishes safety requirements for the proper packaging and transportation of off-site shipments and on-site transfers of hazardous materials, including radioactive materials.
- DOE O 460.2A, *Departmental Materials Transportation and Packaging Management*, invokes DOT requirements or documented requirements providing equivalent safety for on-site shipments.
- DOE M 460.2-1A, *Radioactive Material Transportation Practices Manual,* establishes a set of standard transportation practices for DOE organizations to use in planning and executing off-site shipments of radioactive materials (e.g., radioactive waste), including a framework for interacting with state, Tribal, and local authorities; other Federal agencies; and transportation contractors and carriers regarding DOE radioactive material shipments.

The programs that will be needed to transport grout waste forms from the Hanford Site to either WCS or Energy*Solutions* are identified below:

- General evaluation assumptions and approach
- Key regulatory considerations for packaging and transportation
- Package requirements
- Transportation routes and schedules
- Transportation and disposal costs
- Nonmonetary considerations related to transport
- Risks.

D.3.1 General Evaluation Assumptions and Approach

This study assumes the current status of infrastructure (e.g., railroads, the current regulatory requirements for shipping, and the current shipping and packaging technologies). Basing the analyses on current conditions removes speculation about future conditions while allowing an even-handed comparison of disposal of grout and FBSR waste forms at the off-site disposal facilities. Based on the existing physical capacities of the Clive and WCS facilities, all Class A grout or FBSR LAW waste forms can be disposed of either at Clive or WCS. Based on the existing WCS facility physical capacity, all Class B and C grout waste forms can be disposed of at the WCS disposal facility, in addition to all Class A waste from supplemental treatment.

The use of supplemental LAW feed vectors is introduced in Section D.2.2 for the purpose of predicting the amounts of Class A wastes. A Hanford SP9 1B scenario feed vector is used in the FBSR 1B, Grout 1B, and Grout 2B alternatives. The total liquid volume in this feed vector is 56.2 Mgal. The waste generation period is from January 2034 to February 2076. For off-site transportation purposes, alternatives FBSR 1B, Grout 1B, and Grout 2B were not among the selected alternatives for detailed evaluation.

The Early Start feed vector is used in alternatives Grout 4B and Grout 6, which were evaluated in detail. The total liquid volume in this feed vector is 95.2 Mgal. The waste generation period for this feed vector is from March 2028 to November 2064.

Several figures and tables in Section D.3 were extracted from Volume II, Appendix H, which has a detailed discussion of transportation considerations, including costs for the alternatives entailing off-site disposal. Appendix H also evaluated considerations with both the SP9 1B and Early Start feed vectors. Where tables or figures from that appendix included both feed vectors, they were retained in this appendix for consistency purposes; however, as noted above, the SP9 1B feed vector does not apply to the two alternatives evaluated in detail that entail off-site disposal.

D.3.2 Key Transportation Regulatory Considerations

DOE incorporates appropriate requirements from the NRC concerning the regulation of the packaging for the transport of radioactive materials, and the DOT coordinates with the NRC to set rules for the packaging. The DOT also works with the NRC and affected states to regulate their transport.

10 CFR 71 Packaging and Transportation of Radioactive Materials

10 CFR 71, "Packaging and Transportation of Radioactive Material," defines the packaging and transportation performance criteria to ensure the safe transport of radioactive materials under normal and hypothetical accident conditions. This NRC regulation uses a graded approach in setting packaging criteria to protect public health depending upon activity and hazard of the material. It establishes three levels of packaging depending upon limits listed in the regulation: (1) industrial packaging (IP), (2) Type A packages, and (3) Type B packages. Working with NRC, the DOT has established categories for radionuclide concentrations that determine the type of packaging to be used. These categories use the term Low-Specific Activity (LSA), with different LSA levels requiring different levels of packaging.

All packages for shipping radioactive material (IP, Type A, or Type B) must be designed and prepared so that under conditions normally incident to transportation, the radiation level does not exceed 2 mSv/hour (200 mrem/hour) at any point on the external surface of the package, and a limit for all packages in a shipment.

The supplemental LAW waste forms meet all the requirements of LSA-II materials and can be transported in industrial package (IP)-2 or IP-3 packaging (Volume II, Appendix H, Section H.5). Shipping in a Type A or/and Type B shipping cask is not expected to be necessary. Additional details on the proposed packages for liquid and solid waste forms are provided in Section H.7.1 of Volume II, Appendix H. A description of the process for determining the specific activity and the type of packaging are in Section H.5 of Volume II, Appendix H.

That section also compares the expected activities of the supplemental LAW feed vectors to the limits for LSA-II and concludes that pretreated supplemental LAW liquids, treated grout waste forms, and FBSR waste forms meet the LSA-II limit for liquids and solids in all off-site disposal alternatives with considerable margin. The LSA requirements for liquids also require determination of total activity of a shipment or conveyance, considering the total number of tankers in a shipment. LSA materials must be nonfissile or be exempt under 10 CFR 71.15, "Exemption from Classification as Fissile Material." Although six exemption criteria are provided, the only criterion applicable for supplemental LAW liquids is the total mass of fissile isotopes ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu must be 2 g or less in a package with radioactive liquids.

Figure D-6 depicts the number of liquid container volumes necessary to remain below the fissile limits and shows that the bulk of shipments can be in 4,000-gal containers or less.

The monthly number of containers with liquids per conveyance was calculated using LSA limits as discussed in Volume II, Appendix H, Section H.5. Figure D-7 shows the monthly number of containers per conveyance for the SP9 1B and Early Start feed vectors.

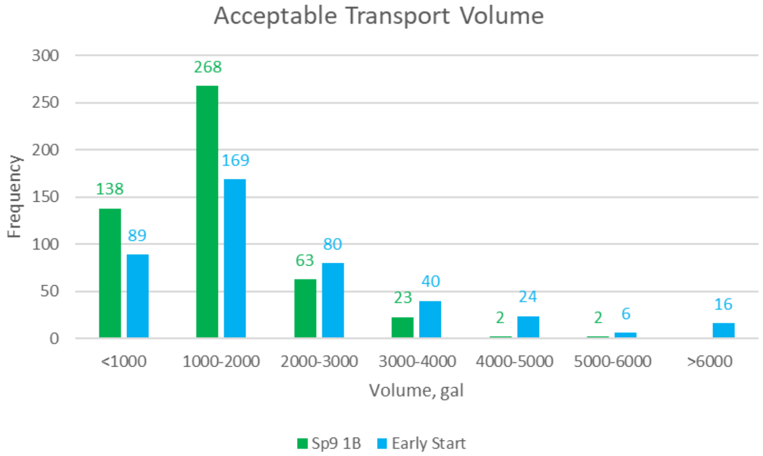


Figure D-6. Liquid Volumes Meeting Nonfissile Exempt for Liquids

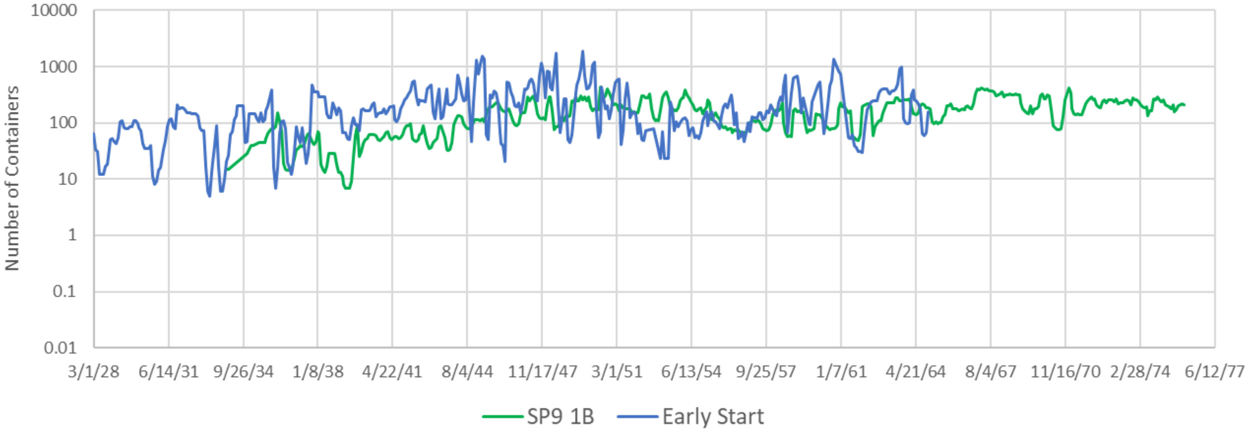


Figure D-7. Number of Containers with Liquids per Conveyance

Figure D-8 presents the same information in the form of a histogram. Based on Figure D-7, 95% (SP9 1B) and 92% (Early Start) of trains can carry 25 containers with liquids (or more) to meet LSA requirements.

The liquid waste treatment capacity, whether at an independent vendor facility, or at Clive or WCS, should be sufficient to process the corresponding annual volumes. The existing licenses at Clive and WCS would need to be amended if larger volumes need to be treated.

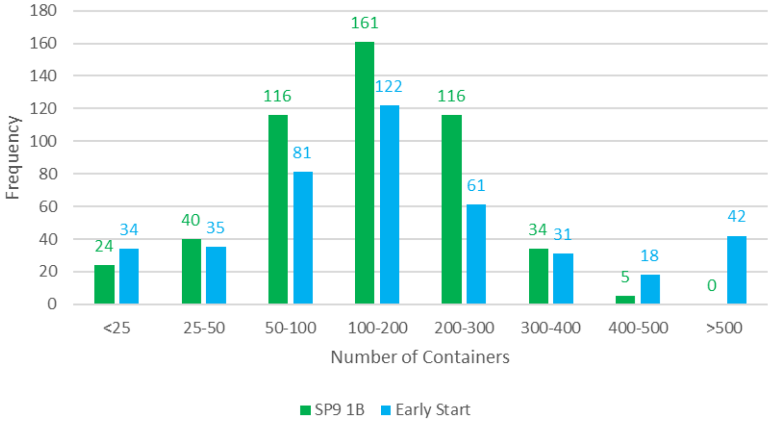


Figure D-8. Number of Containers per Conveyance per Month

External Dose Rates

10 CFR 71.47, “External Radiation Standards for all Packages,” provides requirements for external doses for transportation under LSA packaging:

- Each package of radioactive materials must be designed and prepared for shipment so that under conditions normally incident to transportation, the radiation level does not exceed 2 mSv/h (200 mrem/h) at any point on the external surface of the package, and the highest dose rate 1 m from the source does not exceed 0.1 mSv/h (10 mrem/hr).
- A package that exceeds the radiation level limits above must be transported by exclusive use shipment only, and meet other requirements.

(These are discussed in more detail in Volume II, Appendix H, Section H.5.)

Total monthly activities of the liquid waste form for the SP9 1B and Early Start feed vectors are higher than the total monthly activities of the grout waste form because the radionuclide concentrations are diluted when a grout waste form is generated. Consequently, if liquids meet the dose requirements, the grout waste form will also meet them. In addition to the lower activities, grout is self-shielding, which leads to further lower doses.

Calculations performed using MicroShield for an ISO tank containing radioactive liquids are described in Volume II, Appendix H, Section H.5.3. As shown in Figure D-9, the calculations demonstrate that expected maximum external dose rates from a 5,000-gal ISO tank (conservatively used, though 4,000-gal ISO tanks would be proposed) are below the limits above for the Early Start feed vector.

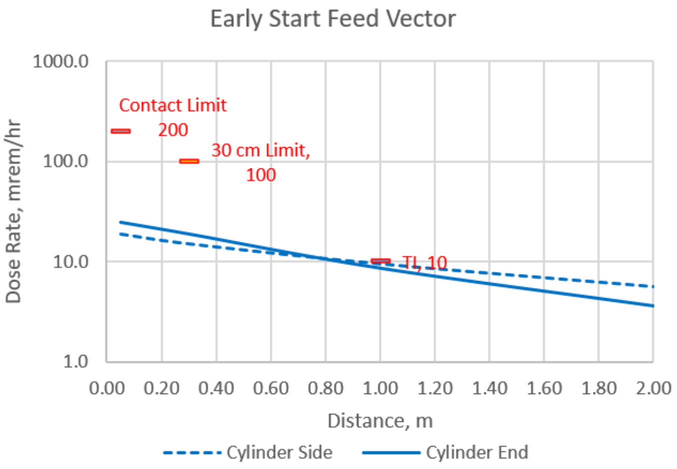


Figure D-9. Maximum External Dose Rates from a 5,000-Gallon ISO Tank with Early Start Feed Vector Liquids

49 CFR 171 – 173 Hazardous Materials Regulations

49 CFR 171–173 address many facets of the transport of radioactive materials, which are a subset of DOT’s broader definition of hazardous materials. Each licensee who transports licensed material on public highways or who delivers licensed material to a carrier for transport must comply with the applicable requirements of the DOT regulations in 49 CFR, “Transportation.” Some of the activities regulated by 49 CFR 171–173 include:

- Packaging: 49 CFR 173, Subparts A, B, and I
- Marking and labeling: 49 CFR 172, Subpart D; and Sections 172.400 through 172.407 and Sections 172.436 through 172.441 of Subpart E
- Placarding: 49 CFR 172, Subpart F, especially Sections 172.500 through 172.519 and 172.556; and appendices B and C
- Accident reporting: 49 CFR 171, Sections 171.15 and 171.16
- Shipping papers and emergency information: 49 CFR 172, Subparts C and G

- Hazardous material employee training: 49 CFR 172, Subpart H
- Security plans: 49 CFR 172, Subpart I.

The DOT regulations also define “contamination” as the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters or 0.04 Bq/cm^2 for all other alpha emitters, while also considering whether the contamination is fixed or non-fixed.

To ensure the appropriate scoping and costing, this study relies on analogous costs from other programs, where DOE has shipped radioactive wastes for disposal (e.g., shipping contaminated soils by rail for disposal). In this way, the scope and cost of meeting the above requirements are captured without summarizing the large number of safety requirements found in 49 CFR 171–173 for shipping radioactive materials.

Other Regulatory Considerations

As noted above, DOE has a set of directives that apply to on-site and off-site transportation. These are not further discussed here.

Actual implementation of a large-scale, off-site disposal program, with the associated transportation program, such as outlined in this appendix (and Volume II, Appendix H), requires additional *National Environmental Policy Act* (NEPA) review.

D.3.3 Off-Site Transportation

Proposed Packaging

DOT requires that LSA materials be transported in packages meeting Type IP-1, Type IP-2, or Type IP-3 packaging criteria (49 CFR 173.411, “Industrial Packages”). 49 CFR 173.427 defines packaging requirements for all types of LSA materials, including the following requirements for LSA-II:

- LSA-II solid materials must be shipped in packages meeting Type IP-2 criteria for both “exclusive” and “non-exclusive” use shipments
- LSA-II liquids must be shipped in packages meeting Type IP-2 criteria for “exclusive” and IP-3 criteria for “non-exclusive” use shipments.

Type IP-2 criteria in turn must meet the general design requirements of 49 CFR 173.410, and when subjected to the tests specified in 49 CFR 173.465(c) (free drop test) and (d) (stacking test) must prevent the (1) loss or dispersal of the radioactive contents, and (2) a significant increase in the radiation levels.

One of the tests, the stacking test, requires that Type IP-2 packages must be able to sustain a compressive load equal to five times the maximum weight of the package for 24 hours without the loss or dispersal of the radioactive contents.

If the supplemental LAW liquids are converted to grout at a separate vendor facility, the grout will have to be transported to Clive and/or WCS for disposal. The IP-2 package proposed for transporting grout and FBSR waste forms is a 8.4 m^3 (11 yd^3) soft-side container. The dimensions of each container will be 2.79 m long × 2.23 m wide × 1.35 m high (110 in. long × 88 in. wide × 53 in. high). To facilitate handling and to provide a rigid form for filling the soft-side containers with grout, the IP-2 soft side containers) can be placed in shipping boxes that can be disassembled. The waste form would remain in the soft-side container and be emplaced as bulk waste if Class A at Clive and/or WCS or in a modular concrete canister (MCC) at WCS if Class B or C.

Two 8.4-m^3 bags will fit into one MMC. Figure D-10 shows an example of a large soft-side container that can be used to ship LSA materials. Conceptually, the shipping box might look like the one shown in Figure D-11, but lighter weight and with a shallower lid.

Source: PacTec, Inc. literature.

Figure D-10. Example of Soft Side Container for Shipping Low-Specific Activity Materials

D.3.4 Transportation Campaign Schedule

Unit trains will likely be used for transport of supplemental LAW. A unit train, also called a block train, is a train in which all cars carry the same commodity and are shipped from the same origin to the same destination, without being split up or stored en route. Unit trains can transport more than 90 rail cars of one type of freight in one car type for one destination, allowing rail cars to bypass intermediary rail yards and run directly from the origin to destination.

Source: Container Technologies Industries, LLC literature.

Figure D-11. Example of a Shipping Box Used for Solid Waste Transport

Liquid Waste Transport

As discussed in Volume II, Appendix H, Section H.5, the volume of liquid waste that can be transported per month is restricted by the acceptable volume that meets the LSA nonfissile material exemption. This volume varies from month to month and exceeds 4,000 gal only in a few months (see Figure D-6). Consequently, a 4,000-gal ISO container was recommended. This information can be used to calculate the number of trains per month that are needed to transport liquids by rail. The transport by a trailer option is only limited by the volume of liquids per container because only one container is transported in a single conveyance.

The number of trains per month was calculated from the monthly feed vector liquid volume, acceptable container volume meeting nonfissile material classification, and the number of containers per conveyance meeting fissile limits. Note that if the number of containers per train meeting fissile limits was greater than 50, then 50 containers per train was assumed as a realistic number of containers in a dedicated train. Figure D-12 shows the monthly number of trains for the SP9 1B and Early Start feed vectors.

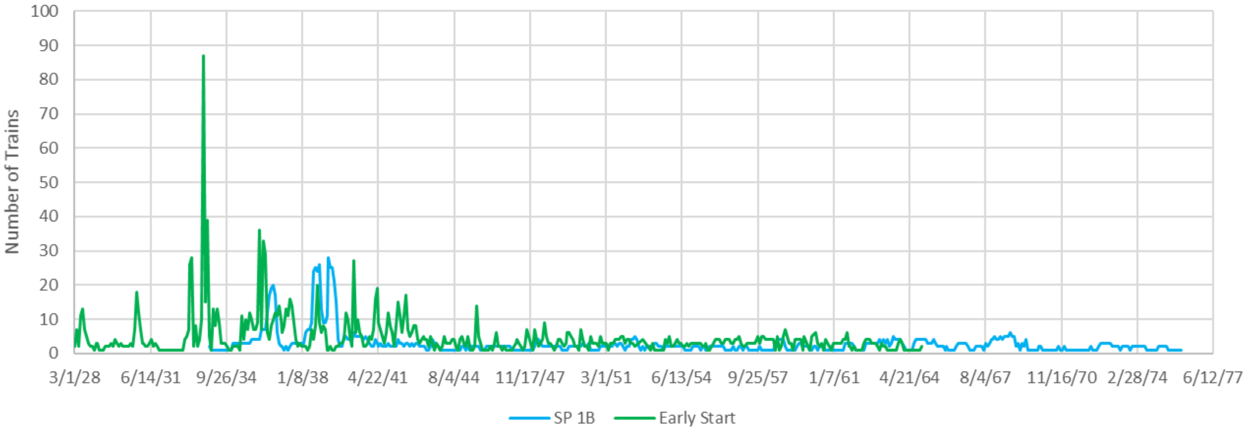


Figure D-12. Number of Trains per Month Required to Transport the Monthly Liquid Volumes

Figure D-13 presents the same information in a histogram. Based on the data presented in Figure D-13, in 79% (Early Start) of the cases, less than five trains per month will be required to transport the liquids. In 21% (Early Start) more cases, five trains or more per month will be required.

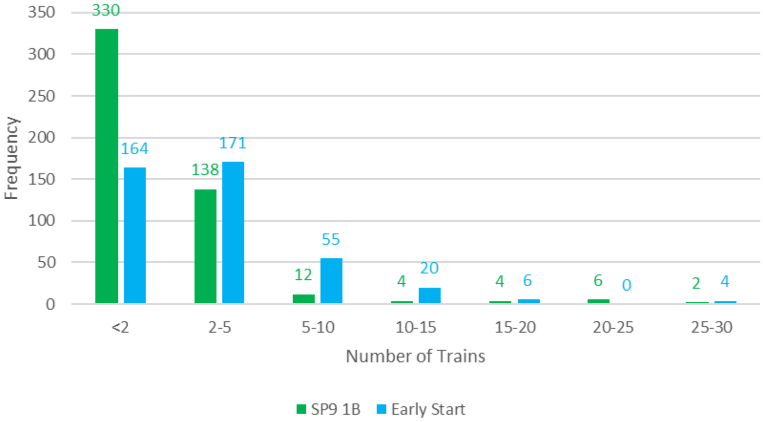


Figure D-13. Number of Trains per Months Histogram

The number of gondolas per month required to transport the generated mass of grout was calculated from the monthly mass of grout generated from the Early Start liquid feed vector assuming six soft-sided bags of grout. Figure D-14 shows the statistics of the calculated number of gondolas in these cases (number of FBSR gondolas are also shown). The number of gondolas per month varies from 1 to 120 for the grout Early Start feed vector. Consequently, only one train per month would be required for grout, with the exception of a few months in grout Early Start. Details of this analysis are in Section H.7.2 of Volume II, Appendix H.

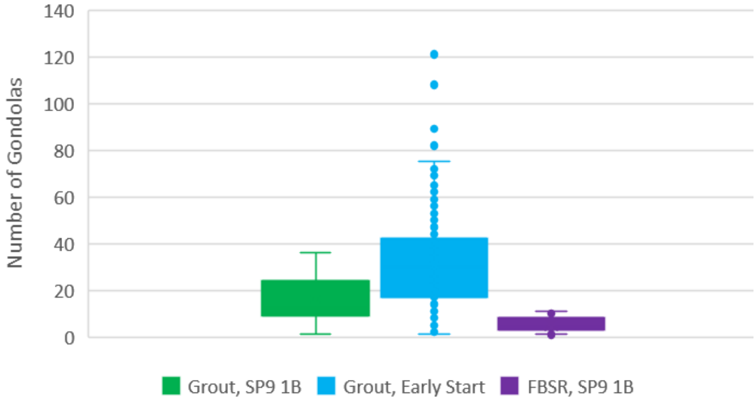


Figure D-14. Number of Gondola per Month Required to Transport Grout or Fluidized Bed Steam Reforming Waste Forms Offsite

D.3.5 Transportation Routes

Figure D-15 is a map of possible rail routes from the Hanford Site to WCS and Clive. The rail routes shown in Figure D-15 were generated with WebTRAGIS, the Oak Ridge National Laboratory routing tool, assuming a dedicated train. The route to WCS ends at the Eunice, New Mexico, rail node. WCS will send their locomotive the short distance to Eunice, New Mexico, to bring the railcars to their facilities in Texas. The route to Clive ends at the Clive facility.

Using the default parameters for route selection in WebTRAGIS yields the route through Oregon, northern California, and Nevada for shipments from Hanford to Clive. When shipments are made, the shipping company and the railroads determine the actual route to use based on many considerations. One possible alternate route is shown through Idaho and Montana in Figure D-16. This route is 1,481 mi, which is slightly longer than the default route (1,213 mi). The analyses presented here are based on using the default WebTRAGIS route. The results based on the alternative route would be similar due to small variations in the route distance and population along the route. Similar alternate routes can also be identified for WCS.

Figure D-15. Rail Routes from Hanford to Waste Control Specialists (Texas) and Clive (Utah)

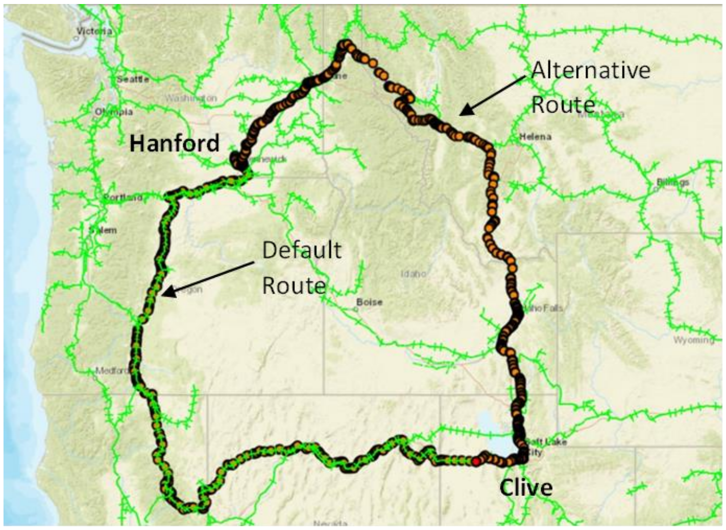


Figure D-16. Default and Alternative WebTRAGIS Routes from the Hanford Site to Clive, Utah

Table D-2 and Table D-3 summarize the route data for the default routes. Table D-4 provides a comparison of the two WebTRAGIS default routes.

Table D-2. Route to Waste Control Specialists (Texas) Waste Disposal Facility Summary

State	Rural Population per mi^2	Rural Distance mi	Suburban Population per mi^2	Suburban Distance mi	Urban Population per mi^2	Urban Distance mi
Colorado	24.6	325.3	1,228.7	100.86	5,336.1	17
Idaho	56.1	63.4	617.9	18.35	0	0
Montana	24.8	562.49	910.8	87.53	5,778.6	7.05
Nebraska	8.9	157.85	809.5	11.01	0	0
New Mexico	9.1	29.77	468.3	2.62	0	0
Oklahoma	21	41.82	280.6	0.99	0	0
South Dakota	13	47.8	253.4	1.09	0	0
Texas	20.4	495.28	976.7	110.66	4,414.3	7.01
Washington	22.6	130.86	1,429.2	48.41	4,674	6.32
Wyoming	15.8	209.55	1,142.9	19.43	3,462	0.54
Total	**21.83**	**2,064.12**	**1,060.37**	**400.95**	**5,110.92**	**37.92**

Table D-3. Route to Clive Disposal Facility (Utah) Summary

State	Rural Population per mi^2	Rural Distance mi	Suburban Population per mi^2	Suburban Distance mi	Urban Population per mi^2	Urban Distance mi
California	10.6	266.71	411.4	7.86	0	0
Nevada	8.7	410.28	784.5	14.5	3,988	1.13
Oregon	21.7	275.71	756.7	40.28	4,968.1	3.57
Utah	2.4	48.06	997	1.13	0	0
Washington	10.7	118.99	1462.5	24.07	3,996.9	1.2
Average/Total	**12.30**	**1,119.75**	**926.89**	**87.84**	**4,582.85**	**5.90**

Table D-4. Route Comparison

Route Parameter	Route to WCS (Texas)	Route to Clive (Utah)
Total population, persons	1,779,152	341,089
Total distance, mi	2,502.99	1,213.49
Average speed, mi/hr	36	23
Number of states crossed	10	5
Number of rail companies	2	1
Number of large cities	5	3
Max population density, persons/mi^2	5,778.6	4,968.1
Average rural population density, persons/mi^2	21.8	12.3
Average suburban population density, persons/mi^2	1,060	927
Average urban population density, persons/mi^2	5,111	4,583
Total rural distance, mi	2,064.12	1,119.75
Total suburban distance, mi	400.95	87.84
Total urban distance, mi	37.92	5.9

Section H.7.3 of Volume II, Appendix H provides an analysis of relative population doses from the projected shipments to both sites. The relative population doses (person-rem) per shipping of one soft-side container are 1.16E-05 (route to WCS) and 3.7E-06 (route to Clive). The difference is due to the larger distance to WCS and higher population densities along the route.

D.3.6 Costs

The off-site disposal costs include transportation and disposal costs. When the liquid feed is converted to grout at an off-site facility, there is also a cost of producing the grouted waste form. The total cost will depend on the split of the Class A waste between Clive and WCS. Total costs were calculated for no split cases (all Class A goes to Clive or to WCS) and for 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 fractions of Class A waste going to Clive.

Rail shipping rates are confidential and there are no "look-up tables" to assess the shipping costs. The rates provided by Perma-Fix Northwest, Inc. (Perma-Fix) for shipment to WCS were used, based on numerous prior rail shipments made by Perma-Fix. The rates are $14,000 per loaded gondola and $5,000 for return of the empty gondola. Because the distance to Clive is about half the distance to WCS, the cost of shipping a loaded gondola to Clive is assumed to be half the cost of shipping a loaded gondola to WCS. The cost of the return shipment of an empty gondola is assumed to be the same. The costs of transporting an ISO container is $3,720 (WCS) and $1,860 (Clive). The costs of transporting an empty ISO container either to WCS or to Clive was assumed to be $1,328 empty, based on the same cost ratio as for the loaded-to-empty gondola transportation cost ratio for WCS.

The disposal cost of the bulk Class A waste at Clive is $886.99/yd^3 (Dempsey, 2022) or $1,160.14/m^3. The disposal cost of the bulk Class A waste and Class B and C waste at WCS are $1,460/m^3 and $7,830/m^3, respectively (SRNL-RP-2018-00687, *Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation*). These costs were used in the calculations of the disposal costs.

The cost of grouting the waste varies depending on where the waste is grouted.

- The cost of off-site grout generation provided by Perma-Fix is $40/gal (Grondin, 2022). For the purpose of the cost estimate, an off-site vendor was assumed to offer grout generation at a similar cost. This cost was used as the rationale for setting the maximum grout generation cost to $45/gal of liquid treated.
- The cost of converting liquid into Class A grout and disposal of grout at Clive is $37.68/gal (Energy*Solutions*, 2019). Converting the disposal costs on a per cubic yard basis to a cost per gallon, the cost of grouting is estimated to be $30/gal.
- Finally, the minimum expected cost of grout generation, based upon a contract for grouting large volumes of LAW on the Hanford Site, is $20/gal (GAO-17-306, *Opportunities Exist to Reduce Risks and Costs by Evaluating Different Waste Treatment Approaches at Hanford*).

Consequently, the calculations were performed assuming $20, $30, and $45/gal of grout generation.

The results of the cost calculations are summarized in Table D-5 and Table D-6 and are plotted on the following pages in Figure D-17 through Figure D-20. In these calculations, the liquid feed is assumed to be converted to grout at a vendor facility and then transported to Clive or/and WCS for disposal. In addition to the total costs, the percent of the annual budget is also calculated, assuming a benchmark annual budget of $450 million dedicated to the supplemental treatment of LAW. The total cost variation from the case when all Class A waste is disposed of at Clive, compared to the case when all Class A waste is disposed of at WCS, ranges from 3.8 to 7.9%. The total cost variation from the case when 50% of Class A waste is disposed of at Clive, compared to the case when all Class A waste is disposed of at WCS, ranges from 2.0 to 5.0%.

Consequently, cost is not a significant differentiator, as discussed below where the total costs include grouting costs, transportation costs, and disposal costs. The case in which off-site disposal only occurs until 2040 corresponds to alternative Grout 6 evaluated in this study.

- For the Early Start feed vector liquid converted to grout at an off-site vendor facility and then transported to Clive and/or to WCS for disposal, the total cost ranges from $3.11 billion to $5.76 billion and represents 18.7% to 34.6% of the benchmark annual funding level of $450 million (Table D-5).
- For the Early Start feed vector liquid converted to grout at a vendor facility and then transported to Clive and/or to WCS for disposal until 2040, the total cost ranges from $1.13 billion to $1.97 billion and represents 21.0% to 36.5% of the benchmark annual funding level of $450 million (Table D-6). The percent of total cost is similar, while the total cost is lower because this is a 12-year campaign compared to a 37-year campaign in Early Start with all waste disposed of offsite.

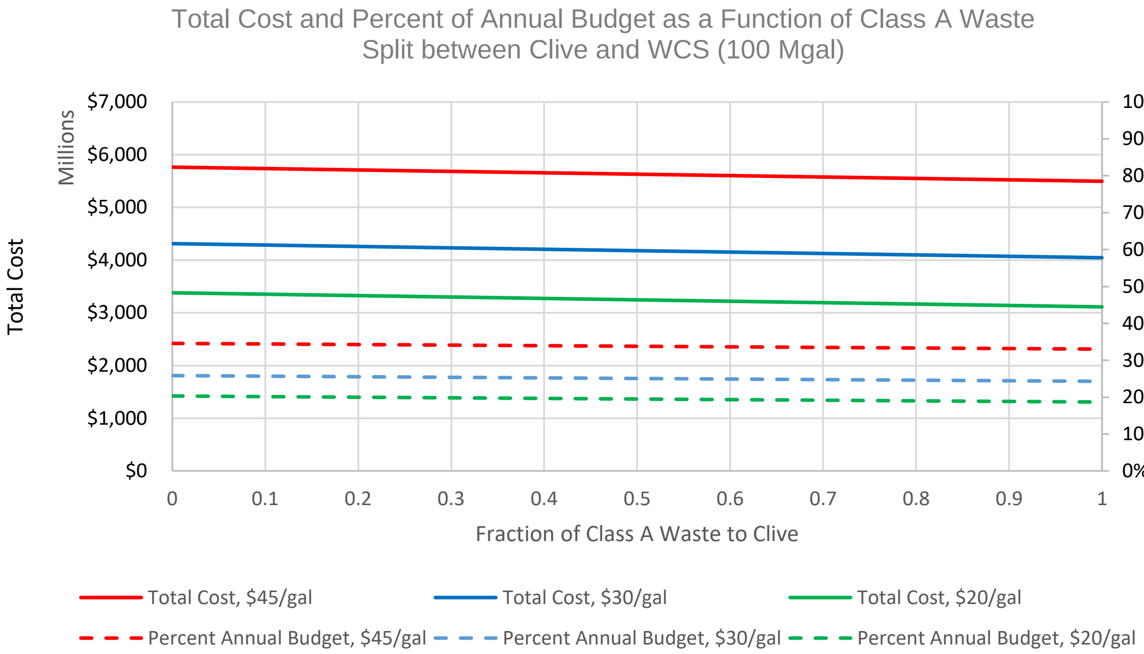
Table D-5. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting by a Vendor

Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$5,760,813,526	34.6%	$4,310,836,837	25.9%	$3,379,881,053	20.30%
0.1	$5,734,306,379	34.4%	$4,284,329,689	25.7%	$3,353,373,906	20.14%
0.2	$5,707,768,231	34.3%	$4,257,791,542	25.6%	$3,326,835,758	19.98%
0.3	$5,681,261,083	34.1%	$4,231,284,394	25.4%	$3,300,328,611	19.82%
0.4	$5,654,722,936	34.0%	$4,204,746,247	25.3%	$3,273,790,463	19.66%
0.5	$5,628,203,788	33.8%	$4,178,227,099	25.1%	$3,247,271,316	19.50%
0.6	$5,601,696,641	33.6%	$4,151,719,952	24.9%	$3,220,764,168	19.34%
0.7	$5,575,158,493	33.5%	$4,125,181,804	24.8%	$3,194,226,020	19.18%
0.8	$5,548,639,346	33.3%	$4,098,662,656	24.6%	$3,167,706,873	19.03%
0.9	$5,522,132,198	33.2%	$4,072,155,509	24.5%	$3,141,199,725	18.87%
1	$5,495,594,050	33.0%	$4,045,617,361	24.3%	$3,114,661,578	18.71%
Max Increase	**4.60%**		**6.15%**		**7.85%**	

Table D-6. Off-Site Grout Disposal Costs, Early Start Feed Vector, Grouting by a Vendor, Off-Site Disposal until 2040

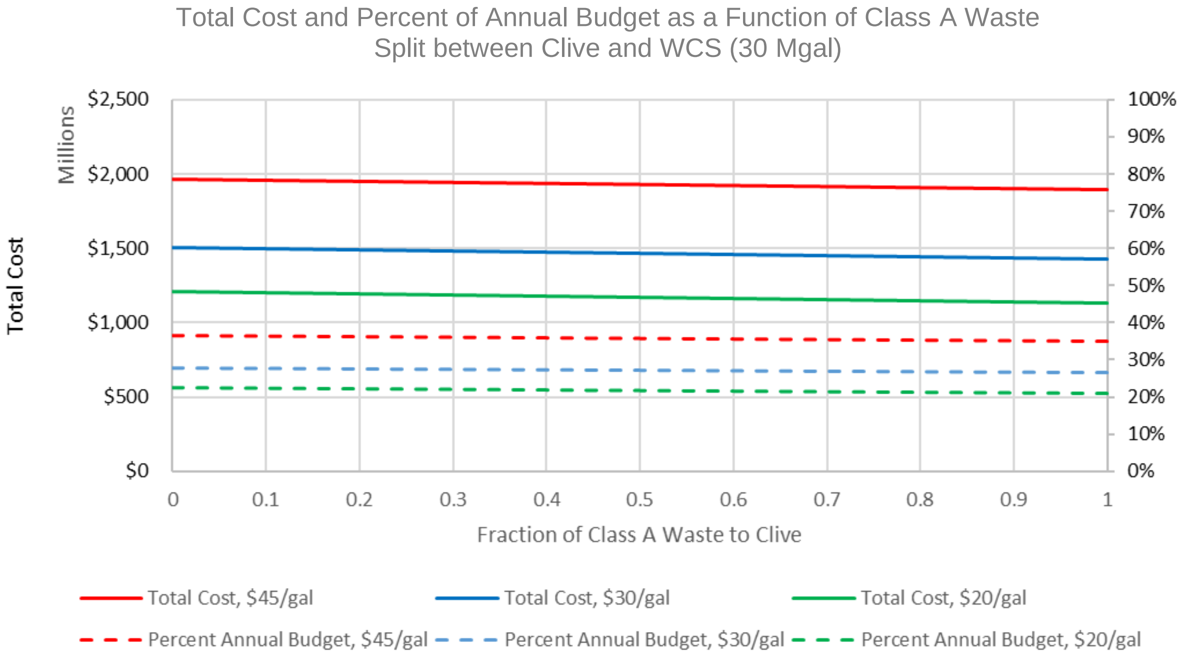
Percent to Clive	$45 per gal	% Annual Budget	$30 per gal	% Annual Budget	$20 per gal	% Annual Budget
0	$1,968,654,218	36.5%	$1,506,303,160	27.9%	$1,209,451,221.71	22.40%
0.1	$1,961,119,385	36.3%	$1,498,768,328	27.8%	$1,201,916,388.96	22.26%
0.2	$1,953,553,553	36.2%	$1,491,202,495	27.6%	$1,194,350,556.21	22.12%
0.3	$1,946,018,720	36.0%	$1,483,667,662	27.5%	$1,186,815,723.46	21.98%
0.4	$1,938,452,887	35.9%	$1,476,101,829	27.3%	$1,179,249,890.71	21.84%
0.5	$1,930,918,054	35.8%	$1,468,566,997	27.2%	$1,171,715,057.96	21.70%
0.6	$1,923,371,222	35.6%	$1,461,020,164	27.1%	$1,164,168,225.21	21.56%
0.7	$1,915,805,389	35.5%	$1,453,454,331	26.9%	$1,156,602,392.46	21.42%
0.8	$1,908,270,556	35.3%	$1,445,919,498	26.8%	$1,149,067,559.71	21.28%
0.9	$1,900,704,723	35.2%	$1,438,353,666	26.6%	$1,141,501,726.96	21.14%
1	$1,893,169,891	35.1%	$1,430,818,833	26.5%	$1,133,966,894.20	21.00%
Max increase	**3.83%**		**5.01%**		**6.24%**	

Figure D-17 through Figure D-20 compare the transportation, disposal, and grout generation costs. The grout generation costs are the highest ones, reflecting the $20/gal to $45/gal treatment cost range, and the transportation costs are the lowest contributors to total cost. This explains why the total cost only slightly increases when all Class A grout is disposed of at WCS.



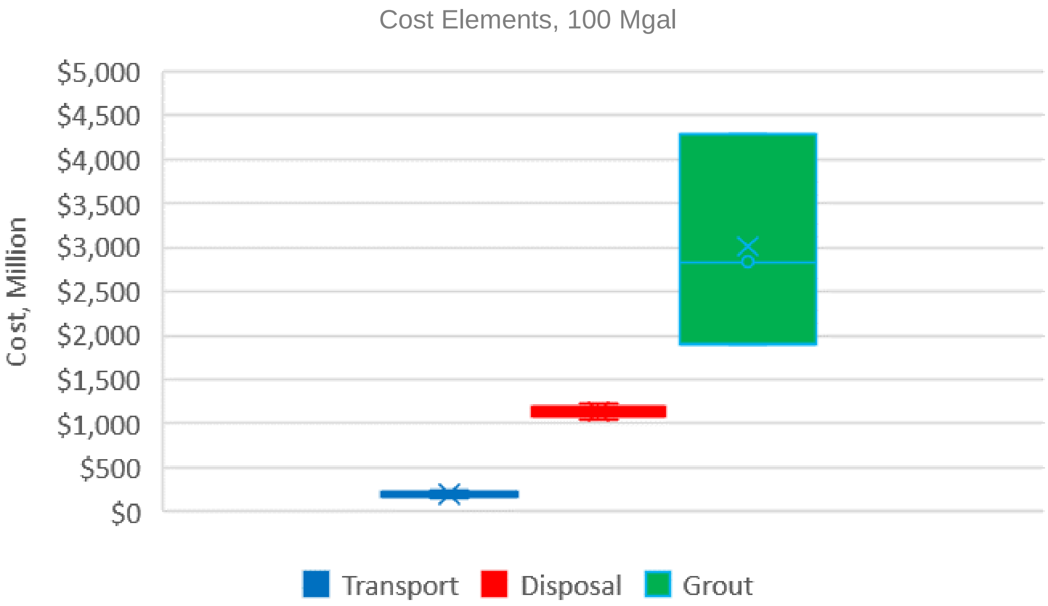
Note: 100 Mgal refers to the total volume of the liquid feed.

Figure D-17. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector



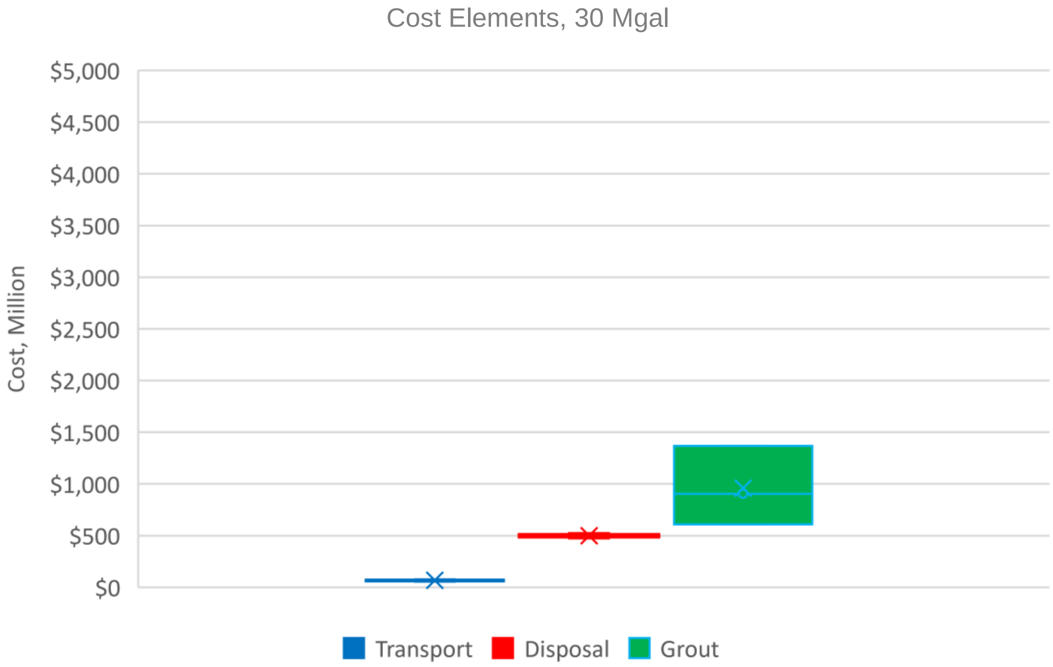
Note: 30 Mgal refers to the total volume of the liquid feed.

Figure D-18. Total Grout Disposal Cost and Percent Annual Budget, Early Start Feed Vector, Disposal until 2040



Note: 100 Mgal refers to the total volume of the liquid feed.

Figure D-19. Grout Disposal Cost Elements, Early Start Feed Vector



Note: 30 Mgal refers to the total volume of the liquid feed.

Figure D-20. Grout Disposal Cost Elements, Early Start Feed Vector, Off-Site Disposal until 2040

If the liquid supplemental LAW feeds are converted to grout at Clive or/and WCS, the transportation costs will be different while the grout generation and disposal costs will be the same as in Table D-5 and Table D-6. The transportation cost of liquids is higher in the Early Start feed vector than in the Early Start feed vector with off-site disposal until 2040. The difference in liquid transportation costs compared to grout will have small impact on the total cost because the transportation costs are small a fraction of the total costs.

D.3.7 Transportation Risks

The transport of goods by truck and railcar increases the amount of traffic, which increases the likelihood of traffic accidents and fatalities, in addition to increasing impacts to air quality, noise, and infrastructure. Statistically, these impacts are largely proportional to the number of miles traveled and independent of the cargo (i.e., transportation risks of transporting concrete blocks and transporting radioactive grout are the same). However, transporting radioactive materials does incur some additional risks, including potential doses to workers and the public from routine transport and from transportation accidents.

NEPA requires federal agencies to prepare an assessment of potential environmental impacts for major federal-sponsored actions that could impact the environment and other factors. Actual implementation of a shipping program, such as outlined here, would require the development of a NEPA assessment that would detail potential impacts to air quality, ecological resources, historic and cultural resources, noise, the public, and occupational health. Previous environmental impact statements (EIS) prepared for other DOE transportation programs provide analogs for risks for proposed shipping campaigns to WCS or Clive.

As an example, DOE/EIS-0337F, *West Valley Demonstration Project Waste Management Environmental Impact Statement, Final Summar*y (WVDP EIS), provides an example of an EIS for a major transportation program, including the shipping of LLW by rail to a disposal facility. The technical details of this EIS transportation analysis are presented in Appendix D of DOE/EIS-0337F.

Transportation Risks from Hanford to Waste Control Specialists

Many of the non-radiological transportation risks are proportional to the miles traveled, and some of the relative, non-radiological risks can be assessed by scaling the analysis from an analogous EIS of the safety of rail transport of other radioactive wastes. The WVDP EIS includes a non-radiological transportation risk assessment that can be scaled to provide a sense of the relative risks of this transportation program.

The closest analogy from the WVDP EIS to the proposed program to transport immobilized LAW from Hanford to the commercial WCS disposal facility is based on the following in the WVDP EIS: Alternative A, rail transport of all LLW and MLLW from WVDP to Hanford (Hanford was once considered a regional disposal facility for DOE-titled LLW). Specifically, under Alternative A, DOE would ship Class A, B, and C LLW (19,200 m^3) and MLLW (221 m^3) to the potential DOE disposal site in Washington State. Although not an exact match, the two transportation programs are very similar, with both programs assessing the impacts of rail transport of LLW and MLLW over ~2,400 mi.

Transportation impacts for rail transport from the WVDP EIS (DOE/EIS-0337F) for Alternative A for all LLW and MLLW for the 2,614-mi trip are presented in Appendix D, Table D-16 of the WVDP EIS and summarized in Column 3 of Table H-14 of Volume II, Appendix H of this report. The WVDP EIS transportation analysis is based on rail accident rates compiled in 1999 (DOE/EIS-0337F, page D 11). These rates were adjusted for freight train accidents for the periods from 2013 to 2022.

Programmatic Risks

This Fiscal Year 2021 National Defense Authorization Act, Section 3125 (NDAA21-3125) study completed a semi-quantitative assessment of risks, based on an elicitation of subject matter experts. This elicitation of risks identified:

- Initiating scenarios that could result in deviations from the design/operational intent
- The probability of the initiating scenario
- The unmitigated consequences
- The means of mitigating such events
- A probability of a successful mitigation
- The cost and schedule consequences of the mitigation.

This semi-quantitative assessment of risks identified and analyzed one programmatic risk for the off-site transportation program: political opposition in a major city on the rail route following a rail accident causes DOE to temporarily stop the shipping program. Based on experience, the probability of this occurring is low; however, the unmitigated consequences were judged to be very high costs and very high schedule impacts.

The mitigation strategy is to change the rail route or shift to shipping by truck. The probability of mitigation success is very high, and the mitigation consequences were assessed to be low cost and low schedule. To avoid the risk of site-specific interruptions of such shipments, agreements with multiple immobilization and disposal sites are important and should be in effect for any such multi-year or multi-decade campaign.

Another strategy is to ensure that both off-site permits/permit modifications (if any are needed), and agreements with off-site facilities, are in place prior to initiation of any on-site grouting or any shipment of liquid supplemental LAW for off-site treatment/disposal. Such agreements could ideally provide for alternative off-site contingency disposition arrangements in the event that the contracted receiving facility cannot disposition the waste as expected. Currently, Energy*Solutions* and WCS dispose of wastes received from the government, medical facilities, industry, and utilities. Liquid waste that is received is converted to solid waste before disposal. There has not been substantive stakeholder or political resistance to specific waste streams being disposed of at these sites, except for depleted uranium, which DOE proposed to dispose of at the Energy*Solutions* Clive site. Neither of the facilities has ever declined a waste receipt, because both facilities have an ability to treat the waste in case if it does not meet the acceptance criteria. In one case, DOE decided to recall the waste shipment sent for an off-site disposal.

Another programmatic risk considered in the analysis is the potential unavailability of the two off-site disposal facilities for either untreated liquids or solidified LAW. Energy*Solutions* (Clive) typically receives over 28,317 m^3 (1 million ft^3) of LLW for disposal on an annual basis, with some years exceeding 141,584 m^3 (5 million ft^3).

Analysis of the feed vectors for supplemental LAW indicates that approximately 15% of any grouted supplemental LAW generated will be greater than Class A waste, indicating, as analyzed in Section D.3.3, that there is significant flexibility between sending the bulk of either treated or untreated supplemental LAW to either Energy*Solutions* Clive or WCS, Additionally, as noted in Section D.2, the expected volume of waste is not expected to oversubscribe available disposal volume at either site.

DOE’s commitment to safety is integrated into all its activities and requirements, including the transportation of hazardous materials. Annually, about three million radioactive materials packages are shipped in the United States by highway, rail, air, and water. In 2020, DOE made over 3,200 hazardous material shipments, covering a combined distance of over 6 million miles. Since fiscal year 2004, the DOE Office of Environmental Management has completed over 184,000 shipments of radioactive material and waste, including liquid LLW shipments to commercial treatment facilities.

Examples of liquid radioactive waste shipments include:

- The successful closure of the DOE Rocky Flats site in Colorado in 2005 was facilitated by more than 1.5 million gallons of liquid radioactive waste shipments to a permitted/licensed commercial treatment and disposal facility in Clive, Utah.
- In 2017, DOE’s West Valley Demonstration Project in New York shipped approximately 1,000 gallons of liquid LLW by truck to a permitted/licensed commercial facility in Andrews County, Texas, for treatment and disposal.
- In 2012, DOE’s Portsmouth Gaseous Diffusion Plant in Ohio shipped approximately 4,700 gallons of radiologically contaminated aqueous hydrogen fluoride by truck to a permitted/licensed commercial facility in Andrews County, Texas, for treatment and disposal as LLW.
- During the past decade, the Separations Process Research Unit in New York shipped approximately 150,000 gallons of liquid LLW by truck to a permitted/licensed commercial treatment facility in Richland, Washington, for treatment.

In addition, DOE works closely with state, tribal and local jurisdictions on transportation-related topics. Specifically, DOE has established a National Transportation Stakeholder Forum to engage at a national level with these stakeholders regarding DOE’s shipments of radioactive materials and waste. The DOE Transportation and Emergency Preparedness Program conducts courses in emergency preparedness with state, tribal and local emergency responders to ensure that they have the necessary training and tools to respond to any transportation accidents involving DOE radioactive material shipments.

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Appendix E. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

E.1 INTRODUCTION

The Federally Funded Research and Development Center (FFRDC) team developed the crosswalk in Table E-1 to confirm that all criteria from Section 3125 of the *National Defense Authorization Act for Fiscal Year 2021* (NDAA21) were addressed in the FFRDC analysis and to indicate where in the taxonomy of decision-informing criteria each NDAA21 element was evaluated.

E.2 CROSSWALK

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 element	FFRDC Report Taxonomy Criteria[b]
3125(c)(1)(A): The maturity and complexity of the technology	Criterion 3.1.1.2: Process complexity Criterion 3.1.1.5: Technology maturity
3125(c)(1)(B): The extent of previous use of the technology	Criterion 3.1.1.5: Technology maturity
3125(c)(1)(C): The lifecycle costs and duration of use of the technology	Criterion 2.1: Specific risks or benefits related to ongoing tank degradation Criterion 2.4: Duration Criterion 3.2: Likelihood and consequences of failing to complete due to resource constraints Criterion 4: Lifecycle costs (discounted present value)
3125(c)(1)(D): The effectiveness of the technology with respect to immobilization	Criterion 1.1.2: Mobility of primary and secondary wastes to a groundwater source Criterion 1.2.2: Confidence in immobilization with regard to groundwater
3125(c)(1)(E): The performance of the technology expected under permanent disposal	Criterion 1.1: Residual threat to health and environment upon successful completion Criterion 1.2: Long-term risks upon successful completion
3125(c)(1)(F): The topical areas of additional study required for the grout option identified in [the prior report]	Volume II, Appendix A provides details of additional studies considered and incorporated into the scoring against the taxonomy criteria.
3125(c)(2): The differences among approaches	Comparison of top-level assessed criteria scores, as presented in Section 5.0 of the report.
3125(c)(3): The compliance of such approaches with the technical standards described in 3134(b)(2)(D) of the FY 2017 NDAA[c] (i.e., CERCLA, RCRA, Clean Air and Clean Water Acts)	Criterion 1.1: Residual threat to health and environment upon successful completion Criterion 1.2.2: Confidence in immobilization with regard to groundwater Criterion 2.2: Risks to humans (during construction and operations) Criterion 2.3: Risks to the environment (during construction and operations) Criterion 5: Securing and maintaining necessary permits/authorities (regulatory approval)

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 element	FFRDC Report Taxonomy Criteria[b]
3125(c)(4): The differences among potential disposal sites for the waste form produced through such treatment	Assessed throughout the taxonomy on an alternative-by-alternative basis for effectiveness, risk, and regulatory impacts. Geological differences were primarily assessed under 1.1 and 1.2; transportation and handling risks were assessed under 2.2 and 2.3.
3125(c)(5)(A): Regulatory compliance	Criterion 1: Long-term effectiveness (environmental and safety risk after disposal) Criterion 5: Securing and maintaining necessary permits/authorities (regulatory approval)
3125(c)(5)(B): Public acceptance	Criterion 6: Community/public acceptance (state/local)
3125(c)(5)(C): Cost	Criterion 3.2: Likelihood and consequences of failing to complete due to resource constraints Criterion 4: Lifecycle cost (discounted present value)
3125(c)(5)(D): Safety	Criterion 2.2: Risks to humans (other than tank degradation)
3125(c)(5)(E): The expected radiation dose to maximally exposed individuals over time	Criterion 1.2.2: Confidence in immobilization with regard to groundwater Criterion 2.2.1.1: Radiation
3125(c)(5)(F): Differences among disposal environments	Assessed throughout the taxonomy on an alternative-by-alternative basis for effectiveness, risk, and regulatory impacts. Geological differences were primarily assessed under 1.1 and 1.2; transportation and handling risks were assessed under 2.2 and 2.3.
3125(c)(6): How much and what type of pretreatment is needed to meet regulatory requirements regarding long-lived radionuclides and hazardous chemicals	No alternatives were scored that were not assessed as highly likely to meet community standards for the relevant contaminants in the planned disposal site. For some alternatives, this meant that specified pretreatment processes (e.g., technetium and/or iodine removal) were included in the definition of the alternative and in associated cost, schedule, and risk assessments.
3125(c)(7): Whether the radionuclides can be left in the waste form or economically removed and bounded at a system level […] and how to account for the secondary waste stream.	Primary and secondary waste streams were considered in assessment of all criteria. Whether to remove radionuclides through pretreatment was specified as part of the definition of the alternative being assessed.
3125(c)(8)(A): The costs and risks in delays with respect to tank performance over time	Criterion 2.1: Specific risks or benefits related to ongoing tank degradation
3125(c)(8)(B): Consideration of experience with treatment methods at other sites and commercial facilities	Criterion 3.1.1.5: Technology maturity, MOE #2: Demonstrated effectiveness elsewhere (including Test Bed Initiative) and MOE #3: Analogous DOE experience

Table E-1. Crosswalk of NDAA Decision Factors to Taxonomy of Decision-Informing Criteria

H.R. 6395[a] – 995 element	FFRDC Report Taxonomy Criteria[b]
3125(c)(8)(C): Outcomes of the Test Bed Initiative of the Hanford Office of Environmental Management	Criterion 3.1.1.5: Technology maturity, MOE #2: Demonstrated effectiveness elsewhere (including Test Bed Initiative) and MOE #3: Analogous DOE experience

[a] *National Defense Authorization Act for Fiscal Year 2021*, Public Law 116–283, January 1, 2021 (also known as the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021).

[b] The full taxonomy of assessment criteria used in this report is provided in Volume I, Appendix A.

[c] *National Defense Authorization Act for Fiscal Year 2017*, Public Law 114–328, December 23, 2016.

CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act.
DOE = U.S. Department of Energy.
FFRDC = Federally Funded Research and Development Center.
MOE = measure of effectiveness.
NDAA = National Defense Authorization Act.
RCRA = Resource Conservation and Recovery Act.

E.3 REFERENCES

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