A COMPARATIVE EVALUATION OF VITRIFICATION AND EMERGING WASTE TREATMENT TECHNOLOGIES FOR U.S. DEPARTMENT OF ENERGY TANK WASTE

by

Vanessa Leigh Morgan

A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 2026

©COPYRIGHT

by

Vanessa Leigh Morgan

2026

All Rights Reserved

ACKNOWLEDGEMENTS

This paper would not have been possible without the encouragement, confidence, and support of the people who stand behind me every day.

To my husband, thank you for your steady patience, perspective, and belief in me throughout this process. Your willingness to carry extra weight at home, listen through long discussions, and remind me why the work matters made all the difference. I am deeply grateful for your partnership.

To my daughter, thank you for being my constant source of motivation and joy. Your curiosity and bright spirit remind me why growth, perseverance, and learning are always worthwhile. I hope this work shows you that dedication and hard work can turn big goals into reality.

I would also like to sincerely thank my instructor, Dr. Margetts, for her guidance, insight, and thoughtful feedback. Her experience and steady direction strengthened both this paper and my development as a professional. I am grateful for her time, patience, and commitment to academic rigor throughout this process.

TABLE OF CONTENTS

1. INTRODUCTION 1

2. BACKGROUND 3

3. OBJECTIVE 1: LITERATURE REVIEW AND DESCRIPTIVE OVERVIEW OF TREATMENT TECHNOLOGIES 6

Vitrification 6
Grouting 8
Fluidized Bed Steam Reforming 9

4. OBJECTIVE 2: COMPARATIVE ANALYSIS OF TREATMENT TECHNOLOGIES 12

Technical Performance and Waste Acceptance 12
Feed Composition and Chemical Variability 12
Thermal and Operational Management 13
Treatment of Organics and Reactive Species 14
Waste Form Durability and Long-Term Performance 15
Glass Durability in Vitrification 15
Cementitious Waste Form Performance 16
Mineralized Waste Forms from FBSR 16
Regulatory Considerations 17
Operational Complexity and Implementation Risk 20
Infrastructure and Facility Scale 20
Process Control and Sensitivity 21
Secondary Waste and Energy Considerations 22

5. OBJECTIVE 3: RECOMMENDATIONS AND APPLICABILITY FRAMEWORK 23

Applicability by Waste Characteristics 23
Applicability by Regulatory and Disposal Context 24
Infrastructure and Implementation Considerations 25
Integrated Decision Framework 26

6. FINAL RECOMMENDATIONS 27

REFERENCES CITED 29

LIST OF TABLES

Table Page

1. Table 1. Comparative Overview of Treatment Technologies.....11
2. Table 2. Regulatory Framework Affecting Technology Selection..... 19

LIST OF FIGURES

Figure Page

1. Figure 1. Aerial view of above ground storage tank at Savannah River. Photo Credit: Savannah River Site. 2

2. Figure 2. DOE Facilities in the United States. Photo Credit: Department of Energy. 5

ABSTRACT

The United States Department of Energy (DOE) manages millions of gallons of legacy radioactive tank waste generated during nuclear weapons production. Long-term treatment and immobilization of this waste remain among the most technically complex and financially substantial environmental challenges within the DOE complex. Although solidifying waste into glass, also known as vitrification, is widely implemented at sites such as the Hanford Site in Washington state, alternative technologies such as grouting and fluidized bed steam reforming have been deployed or evaluated at other facilities, creating variability in technology selection strategies across sites. However, a comprehensive comparative evaluation of these approaches under consistent decision criteria remains limited. Therefore, my study evaluates DOE tank-waste treatment technologies through structured case analysis of selected DOE sites at Hanford, Idaho National Laboratory in Idaho, and the Savannah River site in South Carolina. I examined regulatory frameworks, waste composition characteristics, performance assessment modeling, lifecycle cost considerations, and long-term stewardship requirements to assess how these factors influence technology selection. Publicly available technical reports, environmental impact statements, and site-specific planning documents were reviewed to identify key decision drivers and performance outcomes. My analysis indicates that vitrification provides superior long-term waste form durability and regulatory defensibility for high-activity waste streams, but it involves substantial capital investment and schedule risk. Grouting and reforming technologies may offer cost and operational advantages for certain low-activity or supplemental waste streams, but present limitations related to long-term performance uncertainty and disposal pathway constraints. Technology selection across DOE sites is strongly influenced by site-specific regulatory agreements, infrastructure maturity, and risk tolerance. My findings support a strategic, risk-informed approach to technology selection that aligns waste characteristics, regulatory commitments, and lifecycle cost considerations. I provide recommendations to enhance decision transparency and improve alignment between technical performance objectives and long-term environmental stewardship responsibilities.

INTRODUCTION

The United States Department of Energy (DOE) is responsible for the management of one of the most complex environmental legacies in the world: millions of gallons of radioactive tank waste generated during decades of nuclear weapons production (Ricciotti et al., 2022). Across the DOE complex, sites such as the Hanford Site, Idaho National Laboratory, and Savannah River Site (Figure 1) face similar challenges but operate under different regulatory agreements, waste compositions, risk profiles, and budget constraints. These differences have led to divergent technology pathways, most notably vitrification, grouting, and fluidized bed steam reforming, each with distinct technical, regulatory, and lifecycle cost implications.

Technology selection for high-level and low-activity tank waste is not simply an engineering decision. It is a long-term risk management strategy shaped by federal and state regulatory drivers, consent-based agreements, performance assessment requirements, and public trust (Luhar et al., 2021). The selection of a treatment method commits the federal government to decades of infrastructure investment and environmental stewardship. At sites such as the Hanford Tank Waste Treatment and Immobilization Plant, vitrification has become the cornerstone of compliance strategy, while other locations have pursued alternative or supplemental technologies to address cost, schedule, or waste form performance considerations (Feng et al., 1996).

My paper evaluates DOE tank waste treatment strategies through structured comparison of selected case studies, with emphasis on regulatory drivers, waste form performance, lifecycle cost, and long-term stewardship implications. The objective is to identify decision actors that

most strongly influence technology selection and to provide recommendations grounded in technical and policy analysis.

The management of radioactive tank waste is ultimately a question of intergenerational responsibility. The technologies chosen today will define environmental risk profiles for centuries. A disciplined, evidence-based comparison of treatment strategies is therefore not optional. It is essential.



Figure 1. Aerial view of above ground storage tank at Savannah River. Photo Credit: Savannah River Site.

BACKGROUND

Management of hazardous and mixed radioactive waste has historically emphasized treatment approaches that reduce immediate risk and enable regulatory compliance (Bates et al., 2023). Broadly, these approaches fall into two conceptual categories: destruction of hazardous constituents and stabilization of contaminants within a solid waste form. Destruction-based processes aim to chemically transform or eliminate hazardous substances, often through high temperature or reactive environments. Stabilization-based processes, by contrast, focus on immobilizing contaminants to limit their mobility and long-term environmental release (*Alternatives for Treating and Disposing of High-Level Waste Could Save Billions of Dollars and Reduce Certain Risks (GAO-24-106989)*, 2024).

For many legacy waste streams, particularly tank wastes containing a complex mixture of radionuclides, salts, metals, and organics, complete destruction of hazardous constituents is either impractical or insufficient as a sole management strategy (*DOE/EIS-0200: Final Programmatic Environmental Impact Statement (June 1997)*, 1997). Long-lived radionuclides, such as trans-uranic elements, cannot be destroyed and must instead be isolated from the environment over extended time horizons (Feng et al., 1996). As a result, the durability and performance of the final waste form become governing considerations. Immobilization through physical encapsulation, chemical bonding, or mineral incorporation is therefore a central design objective for treatment technologies applied to these wastes (United States Government Accountability Office, 2018).

Long-term stability is further constrained by the limited availability of geologic disposal pathways for treated waste. In the US, the Waste Isolation Pilot Plant (WIPP) is currently the only operating deep geologic repository, and its statutory mission is restricted to defense-related transuranic waste (*WIPP Facility Work Plan for Solid Waste Management Units*, 2002). This limitation excludes large categories of legacy tank waste and treated secondary wastes from eligibility. At the same time, the termination of the Yucca Mountain repository program has left the United States without an approved disposal pathway for high-level waste and spent nuclear fuel (Neill et al., 1983). In the absence of a foreseeable alternative, many waste forms must be managed under assumptions of extended interim storage or delayed disposal (*Hanford Waste Vitrification Plant Foreign Alternatives Feasibility Study (DOE/RL-90-09)*, 1990). Under these conditions, confidence in long-term waste form performance becomes critical, as treated materials may remain in engineered systems for longer than originally intended.

Waste stabilization technologies vary pointedly in how immobilization is achieved and in the degree of confidence they offer long-term performance. High-temperature processes such as vitrification incorporate contaminants into a glass matrix, relying on the chemical durability of glass to resist leaching (Abbotts & Weems, 2006). Cementous approaches such as grouting immobilize waste through physical encapsulation and chemical interactions within hydrated mineral phases (Fow et al., 1987). Fluidized bed steam reforming occupies an intermediate conceptual space, combining thermal treatment with mineralization reactions that convert waste constituents into stable crystalline solids (Jantzen et al., 2006). Although these technologies differ in mechanism, each ultimately seeks to produce a waste form that meets regulatory performance objectives for disposal.

Given the diversity of waste compositions, regulatory frameworks, and facility constraints encountered across DOE complexes (Figure 2) and similar sites, no single treatment technology is universally optimal. Technology selection is therefore best informed through comparative evaluation rather than isolated assessment. Therefore, this paper is framed as a comparative evaluation of vitrification, grouting, and fluidized bed steam reforming, with the intent of identifying key strengths, limitations, and decision drivers associated with each approach. By examining these technologies through common evaluation criteria, the analysis aims to support defensible and context-sensitive treatment decisions.

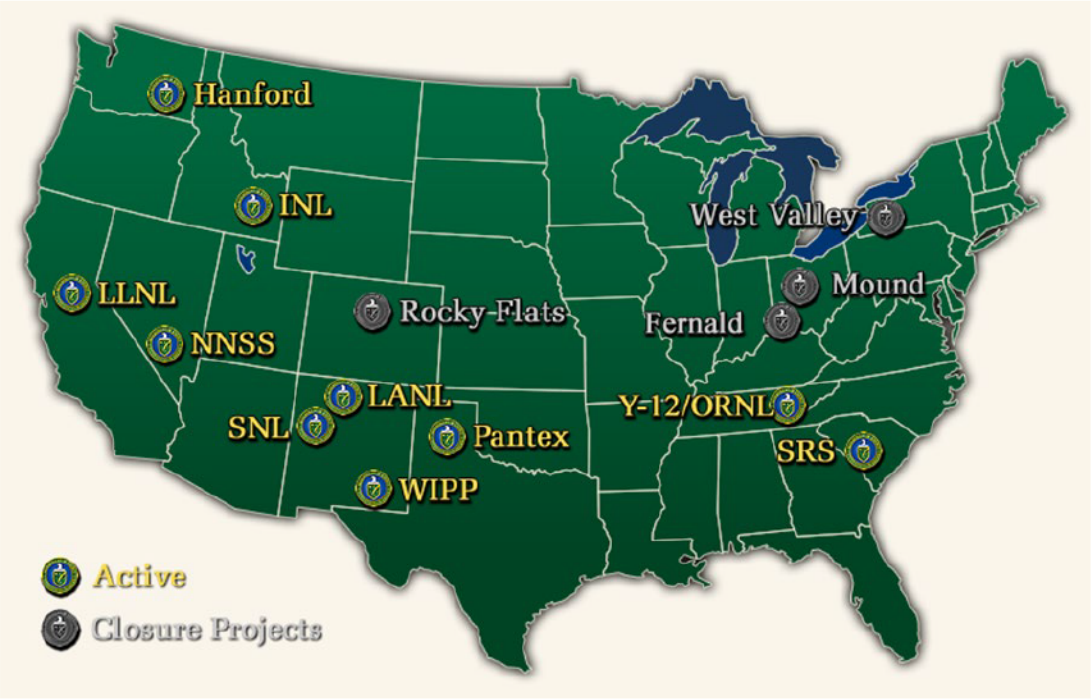


Figure 2. DOE Facilities in the United States. Photo Credit: Department of Energy.

OBJECTIVE 1: LITERATURE REVIEW AND DESCRIPTIVE OVERVIEW OF TREATMENT TECHNOLOGIES

Vitrification

Vitrification is a high-temperature waste treatment process in which waste materials are incorporated into a molten glass matrix. Waste feed is blended with glass-forming additives and heated to temperatures sufficient to produce a homogeneous melt (*Immobilizing Nuclear Waste: Status and Future Developments in Glass and Ceramic Waste Forms,* 2024). Upon cooling, the melt solidifies into a glassy solid that immobilizes contaminants within an amorphous silica-based network. Radionuclides and hazardous metals become chemically incorporated or physically entrapped within the glass structure, reducing their mobility (Feng et al., 1996).

A prominent example of vitrification applied on a scale is the treatment of legacy tank waste at the Hanford Site in Washington State. The Hanford Site, established during the Manhattan Project, generated large volumes of radioactive and chemically hazardous waste that were stored in underground tanks beginning in the 1940s (U.S. Department of Energy, 2024). Over time, these tanks accumulated complex mixtures of high-level radioactive waste, salts, sludges, and organic constituents. The scale and heterogeneity of this inventory present imperative technical challenges for stabilization and long-term disposal (Song et al., 2024).

To address this waste, the DOE constructed the Waste Treatment and Immobilization Plant (WTP) at Hanford. WTP is designed to separate tank waste into high-level and low-activity fractions, each of which is vitrified in dedicated melter systems (U.S. Department of Energy, 2024). The high-level waste fraction is intended for eventual deep geologic disposal, while the

low-activity waste fraction is immobilized in glass for on-site disposal in engineered facilities. The vitrification process at Hanford relies on joule-heated ceramic melters, where electrical current passes through the molten glass to maintain operating temperatures typically exceeding 1100 °C (United States Government Accountability Office, 2018). Off-gas treatment systems capture volatile constituents and control emissions, reflecting the complexity of large-scale high-temperature processing (Bates et al., 2023).

The Hanford vitrification program illustrates several defining characteristics of this technology. First, vitrification can accommodate a wide range of radionuclides and hazardous metals within a durable glass-matrix, supporting long-term performance objectives (Feng et al, 1996). Second, feed composition must be carefully controlled to maintain melt viscosity, prevent crystallization, and manage volatile species (U.S. Department of Energy, 2024). The need for feed pre-treatment, glass formulation development, and robust off-gas systems demonstrates that vitrification is not merely a melting operation but an integrated chemical process requiring extensive engineering controls.

The vitrified waste form produced at Hanford is expected to exhibit high chemical durability and resistance to leaching under repository-relevant conditions (Langton & Hill, 2024). Decades of glass corrosion testing and performance assessment modeling support the projected long-term behaviors of borosilicate glass waste forms (Song et al., 2024). However, the Hanford experience also highlights the scale, infrastructure, and lifecycle commitment associated with vitrification, especially when applied to large and chemically diverse waste inventories.

Grouting

Grouting is a stabilization process that immobilizes waste through incorporation into cementitious materials that harden through hydration reactions. Waste streams are blended with binders such as cement, slag, fly ash, or other binders to produce a slurry (Herbst et al., 1998). As hydration reactions proceed, the slurry cures into a solid matrix composed of hydrated mineral phases that physically encapsulate and chemically bind waste constituents (Fow et al., 1987).

Within the DOE, grouting has been widely applied to low-level and certain mixed radioactive wastes. A notable example is the Saltstone Disposal Facility at the Savannah River Site in South Carolina. At this facility, low-activity salt waste is treated through a process in which decontaminated salt solution is mixed with cementitious materials to form a grout (Wilhite, 1986). The resulting material is pumped into engineered disposal vaults, where it cures into a monolithic solid designed to limit contaminant mobility over time (Kaplan & Thong Hang, 2007).

Grouting has also been used for tank heel stabilization, secondary waste immobilization, and closure of underground tanks and disposal structures across multiple DOE sites (Herbst et al., 1998). Its appeal lies in operational simplicity, adaptability, and compatibility with existing infrastructure. Unlike high-temperature processes, grout-based systems typically operate at ambient temperatures and pressures, reducing energy demands and limiting thermal stress on equipment.

The immobilization mechanisms in cementitious systems are both physical and chemical. Contaminants may be physically encapsulated within the hardened matrix, although certain

species also participate in chemical interactions with hydration products such as calcium silicate hydrates (Lorier & Langton, 2019). Redox conditions, pH, and binder composition play important roles in controlling contaminant solubility and mobility (Luhar et al, 2021). Formulation development is therefore a critical step in ensuring performance for specific waste chemistries, particularly for waste containing high salt concentrations or problematic species such as technetium (Wilhite et al, 1989).

The DOE experience with cementitious waste forms demonstrates that grout can be deployed at large scale with relatively mature construction and process control methods (Wakeley et al., 1991). However, performance of cementitious waste forms is influenced by environmental factors including carbonation, sulfate exposure, and long-term groundwater interactions. As a result, grout-based disposal systems often rely on an integrated approach that combines waste form performance with engineered barriers and site-specific hydrogeologic controls (McDaniel, 1987). These applications illustrate that grouting is not simply a low-cost alternative, but a stabilization method whose effectiveness depends on thoughtful formulation, performance testing, and alignment with disposal system design.

Fluidized Bed Steam Reforming

Fluidized bed steam reforming (FBSR) is a thermal treatment process that converts waste materials into stable mineralized solids through a combination of heat, steam, and chemical additives. In this process, waste is introduced into a fluidized bed reactor containing granular media that is suspended by an upward flow of gas (*DOE/EIS-0391: Final Environmental Impact Statement (November 2012)*, 2012). The fluidized condition promotes uniform temperature

distribution and efficient mixing, enabling controlled chemical reactions throughout the reactor volume (Langton & Hill, 2024).

Within the Department of Energy complex, FBSR was selected for treatment of sodium-bearing waste at Idaho National Laboratory (*DOE/EIS-0200: Final Programmatic Environmental Impact Statement (June 1997)*, 1997). This waste, generated from historic fuel reprocessing operations, consists of acidic liquid waste containing nitrates, sodium salts, radionuclides, and hazardous constituents. The chemical composition and high nitrate content presented challenges for direct vitrification and made alternative stabilization strategies attractive (Jantzen et al., 2006).

To address this inventory, the DOE constructed the Integrated Waste Treatment Unit (IWTU) at Idaho National Laboratory. The IWTU employs a fluidized bed steam reformer designed to thermally treat liquid waste by injecting it into a heated bed along with steam and mineralizing additives such as clay (Mason et al., 2003). Organic constituents are thermally destroyed, while nitrates are reduced under redox conditions. Simultaneously, inorganic components react with additives to form crystalline mineral phases, including aluminosilicate structures intended to immobilize radionuclides and hazardous metals (Ryan et al., 2007). The product of the FBSR process at IWTU is a granular mineralized solid rather than a monolithic glass (Olson et al, 2005). This material is engineered to mimic naturally occurring stable minerals, with the objective of enhancing long-term chemical stability. Following reforming, the granular product is packaged for disposal consistent with applicable regulatory requirements (Simpson, 2024).

The IWTU example illustrates several defining characteristics of fluidized bed steam reforming. First, FBSR can treat nitrate-rich and chemically complex liquid wastes while simultaneously destroying organic constituents (Mason et al., 2003). Second, mineral formation is intentionally engineered through additive selection and process control, meaning the final waste form is the result of targeted chemistry rather than simple encapsulation (Mason et a., 2003). Third, successful implementation requires precise control of operating temperature, redox conditions, feed rate, and bed behavior to ensure consistent product quality (Mason et al., 2003, Mason et al., 2006).

The DOE experience at Idaho demonstrates that FBSR can be applied to specific waste streams that pose challenges for other treatment technologies. At the same time, the scale up and operational history of IWTU highlights the importance of system integration, process control, and validation of mineral waste form performance. Table 1 demonstrates these comparisons.

Table 1. Comparative Overview of Treatment Technologies

Technology	**Waste Form**	**Target Waste Type**	**Chemical Durability**	**Regulatory Complexity**	**Operational Complexity**	**DOE Example Site**
Vitrification	Borosilicate glass	High-level waste	High	High	High	Hanford Site
Grouting	Cementitious	Low-level waste	Moderate	Moderate	Low	Savannah River Site
FSBR	Granular ceramic	Sodium-bearing	High	Moderate	High	Idaho National Lab

OBJECTIVE 2: COMPARATIVE ANALYSIS OF TREATMENT TECHNOLOGIES

My comparative analysis evaluates vitrification, grouting, and fluidized bed steam reforming using common performance criteria derived from regulatory guidance, technical literature, and documented operational experience. Criteria were selected based on their relevance to long-term waste isolation and practical implementation considerations. Although additional factors such as detailed lifecycle cost modeling and site-specific infrastructure constraints are important for technology selection, this analysis focuses on technical performance, waste form durability, regulatory acceptance, and operational complexity due to the availability of published data.

Technical Performance and Waste Acceptance

Technical performance and waste acceptance define the practical boundaries of each treatment technology. Because all three approaches aim to immobilize hazardous and radioactive constituents, they differ substantially in feed flexibility, process sensitivity, and ability to manage chemically complex waste streams.

Feed Composition and Chemical Variability

The Hanford Waste Treatment and Immobilization Plant demonstrates that vitrification can accommodate a broad range of radionuclides and hazardous metals within a borosilicate glass matrix (Abbotts & Weems, 2006). However, the process requires careful feed pretreatment and blending to control melt viscosity, electrical conductivity, and phase behavior (Bates et al., 2023). High concentrations of certain salts, refractory components, or volatile species can affect

melter performance and off-gas management (Feng et al., 1996). As implemented at Hanford, vitrification relies on substantial upstream waste characterization and formulation development to ensure stable operation.

In contrast, cementitious stabilization at the Savannah River Site Saltstone Disposal Facility illustrates the relative feed flexibility of grouting for low-activity liquid wastes (Herbst et al., 1998). Decontaminated salt solution is blended with dry materials to produce a pumpable grout (Fow et al., 1987). Although formulation adjustments are necessary to address specific chemical species and to control set time and curing behavior, the process operates at ambient conditions and is generally tolerant of compositional variability within defined limits.

Fluidized bed steam reforming at the Integrated Waste Treatment Unit was selected in part because of the chemical challenges posed by nitrate-rich sodium-bearing waste (Mason et al., 2003). The FBSR process can reduce nitrates and destroying organic constituents while converting inorganics into mineralized solids (Mason et al., 2006). This ability to chemically transform problematic species distinguishes FBSR from purely encapsulating approaches (Olson et al., 2005). However, achieving consistent mineral formation requires tight control of redox conditions, temperature, and additive ratios, indicating a different kind of process sensitivity compared to vitrification or grout systems.

Thermal and Operational Management

Vitrification operates at temperatures exceeding 1,000 °C, as seen in the joule-heated melters at Hanford (*Hanford Waste Vitrification Plant Foreign Alternatives Feasibility Study (DOE/RL-90-09)*, 1990). This high-temperature regime supports dissolution and homogenization of diverse

waste constituents but necessitates robust refractory materials, off-gas treatment systems, and substantial energy input (Wakeley et al., 1991).

Grouting, by contrast, proceeds at near-ambient temperature and pressure (Wilhite et al., 1989). The Saltstone process illustrates how stabilization can occur through hydration reactions without the need or high thermal input. This reduces energy demand and simplifies equipment requirements, although it also limits the ability to thermally destroy hazardous organics (Kaplan & Thong Hang, 2007).

Fluidized bed steam reforming occupies an intermediate position. At IWTU, elevated temperatures are used to drive thermal decomposition and mineral-forming reactions (Simpson, 2024), but the process operates below the melting point of glass and avoids formation of a molten phase (Ryan et al., 2007). The fluidized bed configuration enhances heat and mass transfer, enabling controlled chemical reactions without producing a monolithic melt (Olson et al., 2005).

Treatment of Organics and Reactive Species

One of the clearest distinctions among the technologies lies in their treatment of organic constituents and reactive salts (*Final Review of the Study on Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation,* 2020). Vitrification thermally destroys most organics within the melt environment, although volatile species must be managed through off-gas systems (Abbotts & Weems, 2006). Grouting does not inherently destroy organics and instead relies on immobilization or prior treatment (Wilhite, 1986). FBSR, as implemented in Idaho, intentionally destroys organics and reduces nitrates under controlled

conditions, converting them into more stable chemical forms before mineral incorporation (Ryan et al, 2007).

Waste Form Durability and Long-Term Performance

Long-term waste form performance is a central criterion for evaluating treatment technologies, particularly considering limited disposal pathways and the potential for extended interim storage. Durability encompasses resistance to chemical degradation, leaching, radiation effects, and environmental interactions over time. The DOE implementations at Hanford, Savannah River, and Idaho National Laboratory illustrate differing approaches to achieving this objective.

Glass Durability in Vitrification

At the Hanford Waste Treatment and Immobilization Plant, vitrification produces borosilicate glass waste forms designed for long-term geologic isolation (Bates et al., 2023). Glass immobilizes contaminants within an amorphous silica network, distributing radionuclides and hazardous metals at the molecular scale (Feng et al., 1996). Decades of corrosion testing and performance modeling for borosilicate glass provide a substantial empirical foundation for predicting long-term behavior (*DOE/EIS-200: Final Programmatic Environmental Impact Statement (June 1997),* 1997).

Glass corrosion in aqueous environments typically proceeds through slow surface alteration and formation of secondary phases (U.S. Department of Energy, 2024). Performance assessments for Hanford glass account for repository-relevant conditions, including groundwater chemistry and temperature (Wakely et al., 1991). Because the immobilization method is intrinsic

to the glass matrix itself, vitrified waste forms are often characterized as possessing high chemical durability independent of engineered barriers (*Hanford Waste Vitrification Plant Foreign Alternatives Feasibility Study (DOE/RL-90-09),* 1990). This intrinsic stability is one reason vitrification has been selected or high-level waste treatment.

Cementitious Waste Form Performance

At the Savannah River Saltstone Disposal Facility, the durability strategy differs. Cementitious waste forms immobilize contaminants within hydrated mineral phases and a porous matrix (Wilhite et al., 1989). The performance of these waste forms depends on maintaining favorable geochemical conditions, particularly high pH, which limits the solubility of many radionuclides and hazardous metals (Wilhite, 1986).

Long-term degradation mechanisms for grout include carbonation, sulfate attack, and changes in redox conditions that may influence mobility of certain species (Wakeley et al., 1989). DOE performance assessments for Saltstone therefore consider not only the waste form itself but also engineered vault systems and site hydrogeology. In this context, durability is achieved through a systems approach: the waste form, disposal structure, and natural environment collectively contribute to long-term containment (Kaplan & Thong Hang, 2007). This distinction is important. Whereas vitrified glass emphasizes chemical durability, grout performance is more tightly coupled to the surrounding engineered and geochemical environment.

Mineralized Waste Forms from FBSR

At the Integrated Waste Treatment Unit, fluidized bed steam reforming produces a granular mineralized product composed of engineered crystalline phases (*DOE/EIS-0391: Final*

Environmental Impact Statement (November 2012, 2012). Additives such as clay are introduced specifically to form aluminosilicate minerals intended to incorporate radionuclides within stable crystal structures (Mason et al., 2006). The design philosophy is to emulate naturally occurring durable minerals, thereby leveraging geologic analogs as a performance basis.

Because the FBSR product is granular rather than monolithic, its long-term performance depends on both the stability of individual mineral phases and the behavior of the consolidated waste form as packaged for disposal (Mason et al., 2003). Laboratory leach testing and mineral characterization support projections of chemical stability; however, compared to borosilicate glass, the operational history and large-scale disposal experience are more limited (Simpson, 2024).

The Idaho National Laboratory case illustrates a hybrid durability strategy. Rather than relying on amorphous glass networks or cement hydration products, FBSR engineers specific crystalline phases to immobilize contaminants (Mason et al., 2003). This approach combines with intentional chemistry with mineralogical stability but requires continued validation to establish long-term predictive confidence comparable to more established waste forms (Ryan et al., 2007).

Regulatory Considerations

Treatment technology for DOE tank waste is fundamentally constrained by federal environmental law, state regulatory authority, and site-specific compliance agreements. At the federal level, the Resource Conservation and Recovery Act (RCRA) governs hazardous waste management, including mixed radioactive waste (Resource Conservation and Recovery Act, 1986). RCRA establishes treatment standards, land disposal restrictions, and permitting

requirements that directly influence whether vitrification, grouting, or mineralizing thermal processes are viable compliance pathways. For DOE sites managing mixed waste, RCRA is often the primary driver of treatment system design. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) also influences treatment decisions at legacy cleanup sites. Under CERCLA, remedy selection must satisfy protectiveness standards and comply with "applicable or relevant and appropriate requirements" (ARARs), which frequently include RCRA treatment standards (Comprehensive Environmental Response, Compensation, and Liability Acy, 1993).

The Atomic Energy Act (AEA) provides DOE authority over radioactive materials, but its implementation must coexist with RCRA where hazardous constituents are present (*Atomic Energy Act and Related Legislation*, 2026). This dual regulatory structure creates a layered compliance framework, particularly relevant at sites such as the Hanford Site and Idaho National Laboratory, where tank wastes are both chemically hazardous and radioactive.

At the state level, delegated RCRA authority meaningfully shapes implementation. In Washington, the Hazardous Waste Management Act grants the state regulatory oversight of RCRA programs at Hanford, making vitrification not only a technical choice but a negotiated regulatory commitment. Similarly, Idaho's Site Treatment Plan and Settlement Agreement constrain treatment timelines and waste disposition pathways at Idaho National Laboratory. In South Carolina, state permitting and consent agreements frame grout-based disposal operations at the Savannah River Site (*Laws and Regulations - Hazardous Waste | South Carolina Department of Environmental Services*, 2025).

Disposal Availability further ensures a tailored approach to regulatory strategy is required. The Waste Isolation Pilot Plant (WIPP), authorized under the Waste Isolation Pilot Plant Land Withdrawal Act, is limited to defense-related transuranic waste and does not provide a disposal pathway for most tank waste streams (*WIPP Facility Work Plan for Solid Waste Management Units, 2002)*. The absence of a license geologic repository for high-level waste under the Nuclear Waste Policy Act creates long-term uncertainty that directly influences waste form durability requirements and interim storage strategies (Nuclear Waste Policy Act, 1982).

Table 2. Regulatory Framework Affecting Technology Selection

Statute	**Governs**	**Impact on Design**	**DOE Site Example**
Resource Conservation and Recovery Act (RCRA)	Hazardous/mixed waste	Treatment standards and land disposal restrictions	Hanford, Idaho
Atomic Energy Act (AEA)	Radioactive materials	DOE authority over HLW	All sites
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	Cleanup remedies	ARAR compliance and protectiveness standards	Hanford
State Law	Permitting and enforcement	Consent decrees, milestones	All sites

Accordingly, regulatory and disposal considerations are not downstream constraints. They are primary drivers. Treatment technologies must be selected not only for technical performance, but for defensibility within a complex statutory and state-federal regulatory structure that ultimately governs what can be permitted, constructed, and closed (Table 2).

Operational Complexity and Implementation Risk

Operational complexity and implementation risk are critical considerations in large-scale waste treatment programs. These factors include infrastructure requirements, process control demands, startup challenges, energy intensity, and long-term maintenance obligations. The DOE implementations at Hanford, Savannah River, and Idaho National Laboratory illustrate markedly different operational profiles.

Infrastructure and Facility Scale

The Waste Treatment and Immobilization Plant at the Hanford Site represents one of the most complex nuclear construction projects undertaken within the DOE complex (U.S. Department of Energy, 2024). Vitrification at Hanford requires large-scale pretreatment systems, high-temperature ceramic melters, extensive off-gas treatment trains, and robust shielding and containment systems (Langton & Hill, 2024). The integration of waste retrieval, pretreatment, vitrification, and canister handling creates a tightly coupled system in which delays or design modifications in one area can propagate across the facility (Song et al., 2024). This scale reflects the intrinsic demands of high temperature melting and radioactive waste handling. The infrastructure required for vitrification is substantial, and capital investment is correspondingly high (Sanito et al., 2022). However, the system is designed for long operational life and high-throughput processing of diverse tank wastes (Song et al., 2024).

In contrast, the Saltstone Disposal Facility at the Savannah River Site demonstrates a comparatively streamlined operational model. Grouting operations involve blending liquid waste with dry cementitious materials and pumping the slurry into engineered vaults (Fow et al., 1987). While formulation control and curing conditions must be managed, the process avoids high-

temperature equipment and complex off-gas systems (Herbst et al., 1998). Facility requirements are more closely aligned with conventional industrial concrete operations, albeit under radiological controls.

The Integrated Waste Treatment Unit at Idaho National Laboratory occupies an intermediate position. FBSR processes require elevated temperatures, controlled redox environments, and precise feed and additive management (Mason et al, 2003). The reactor system, gas handling components, and product packaging infrastructure introduce complexity beyond that of grout operations. At the same time, the absence of a molten phase reduces certain material and energy use challenges associated with vitrification (Jantzen et al., 2006).

Process Control and Sensitivity

Vitrification systems, such as those at Hanford, demand careful control of feed composition, melter temperature, and electrical parameters to maintain stable glass production (Langton & Hill, 2024). Off-gas systems must manage volatile radionuclides and hazardous constituents, requiring continuous monitoring and filtration (Bates et al., 2023). Deviations in feed chemistry can affect melt behavior and product quality, necessitating detailed characterization and blending strategies (*Alternatives for Treating and Disposing of High-Level Waste Could Save Billions of Dollars and Reduce Certain Risks (GAO-24-106989,* 2024).

Grouting systems exhibit different sensitivities. Key operational parameters include mix ratios, set time, and curing conditions (Lorier & Langton, 2019). While less energy-intensive, grout operations must account for potential variability in waste chemistry that could affect hydration reactions of long-term performance (Fow et al., 1987). The operational envelope is

typically broader than that of high-temperature systems, but formulation control remains essential.

Fluidized bed steam reforming, as implemented at IWTU, requires stable fluidization conditions, controlled temperature, and appropriate redox balance to ensure complete nitrate reduction and formation of target mineral phases (Mason et al., 2006). Process upsets can influence product composition or reactor behavior. Maintaining consistent bed dynamics and feed injection rates is central to reliable operation (Jantzen et al., 2006).

Secondary Waste and Energy Considerations

High-temperature systems such as vitrification generate secondary waste streams associated with off-gas treatment, filtration, and equipment maintenance (Abbotts & Weems, 2006). Energy demand is substantial due to sustained melter operation. Fluidized bed steam reforming also produces secondary streams of gas cleanup systems, though typically at lower peak temperatures than vitrification (Olson et al., 2005). Grouting systems generate comparatively limited airborne secondary waste and operate with lower energy intensity (McDaniel, 1987). However, the total volume of stabilized waste may be greater due to the addition of cementitious materials, influencing disposal capacity requirements (Wakeley et al., 1991).

OBJECTIVE 3: RECOMMENDATIONS AND APPLICABILITY FRAMEWORK

The DOE implementations at the Hanford Site, the Savannah River Site, and Idaho National Laboratory demonstrate that treatment technology is strongly influenced by waste characteristics, regulatory mission, and infrastructure context. The following framework draws on these examples to identify conditions under which vitrification, grouting, or fluidized bed steam reforming are the most defensible.

Applicability by Waste Characteristics

The Hanford task waste program illustrates circumstances in which vitrification becomes a logical choice. The presence of high-level radioactive waste containing long-lived radionuclides, combined with the expectation of eventual deep geologic disposal, places primary emphasis on intrinsic waste form durability (Bates et al., 2023). In this context, the chemical robustness and long-term performance modeling history of borosilicate glass align with disposal objectives that extend over geologic timescales.

At the Savannah River Site, the Saltstone process reflects a different waste profile. Low-activity salt solutions, following radionuclide separation, are immobilized in a cementitious matrix suitable for engineered near-surface disposal. Here, the waste does not require the same degree of intrinsic material durability as high-level waste, and the system-level performance of grout combined with engineered vaults satisfies regulatory criteria (Langton & Hill, 2024). The waste form strategy is aligned with disposal category and hazard level.

At Idaho National Laboratory, the selection of fluidized bed steam reforming for sodium-bearing waste demonstrates applicability where chemical complexity is a primary challenge. High nitrate content and the presence of organics made a mineralizing thermal process attractive. FBSR offered the ability to chemically transform problematic constituents prior to immobilization, creating a mineralized product tailored to the waste chemistry (Herbst et al., 1998).

Taken together, these examples suggest the following guiding principle: when long-lived radionuclides dominate and geologic isolation is anticipated, technologies emphasizing intrinsic material durability may be favored. When activity levels are lower and disposal systems are engineered for near-surface performance, cementitious stabilization may be appropriate. When chemical transformation of reactive species is required before stabilization, mineralizing thermal processes such as FBSR may offer advantages.

Applicability by Regulatory and Disposal Context

Regulatory mission plays a decisive role in technology alignment. At Hanford, vitrification is consistent with federal policy or high-level waste immobilization, even in the absence of an operational geologic repository. The regulatory familiarity of glass waste forms supports long-term performance assessments under anticipated repository conditions.

At Savannah River, the Saltstone Disposal Facility operates within an established low-level waste regulatory framework. The cementitious waste form is evaluated in combination with engineered disposal structures and site hydrology (*Immobilizing nuclear waste: Status and Future Developments in Glass and Ceramic Waste Forms*, 2024). The regulatory pathway is well defined and integrated with the selected stabilization method.

At Idaho National Laboratory, the IWTU product is managed under site-specific regulatory determinations. While technically demonstrated, the relative novelty of FBSR compared to glass or grout may require additional validation depending on disposal destination (Olson et al., 2005). This illustrates that institutional familiarity and precedent can influence implementation risk independent of technical feasibility.

Thus, when disposal pathways are clearly defined and aligned with established waste form precedents, technologies with regulatory familiarity may reduce approval uncertainty. Where disposal pathways are uncertain or evolving, emphasis may shift towards waste forms with strong intrinsic performance characteristics capable of supporting extended interim storage.

Infrastructure and Implementation Considerations

Infrastructure readiness and integration risk further influence defensibility. The Hanford vitrification program reflects a commitment to complex, capital-intensive infrastructure capable of sustained high-throughput operation. Such systems may be justified for large inventories requiring decades of processing, but they entail substantial construction, integration, and operational risk (Song et al., 2024).

The Saltstone model demonstrates that grout-based stabilization can often be implemented with comparatively modest infrastructure, leveraging industrial cement technology under radiological controls. For sites seeking lower capital intensity and operational simplicity, cementitious systems may present fewer implementation barriers.

The IWTU example illustrates an intermediate approach. FBSR requires specialized reactor systems and process controls but avoids the extreme thermal regime of vitrification. The

Idaho National Laboratory experience shows that while technically viable, startup and integration challenges must be anticipated in deployment of complex thermal systems.

A practical conclusion emerges: technology selection should consider not only waste form performance but also institutional capacity to design, construct, maintain, and operate the required systems over program lifetimes that may span decades.

Integrated Decision Framework

The DOE case studies suggest that defensible technology selection emerges from the interaction of three primary decision drivers: (1) Required duration and confidence of waste form performance, (2) chemical and radiological characteristics of the waste stream, and (3) regulatory alignment and infrastructure capability.

Hanford, Savannah River, and Idaho National Laboratory did not converge on a single universal solution because their waste inventories and regulatory contexts differ fundamentally. Each site selected a stabilization strategy that balanced durability, chemical compatibility, regulatory precedent, and implementation risk. Accordingly, no single technology can be characterized as universally superior. Vitrification offers high intrinsic durability and strong regulatory precedent for high-level applications. Grouting provides operational simplicity and compatibility with engineered near-surface disposal systems or lower-activity waste. Fluidized bed steam reforming enables chemical transformation and mineral stabilization of complex waste streams but may require careful integration and validation.

Future decisions should incorporate site-specific performance modeling, lifecycle analysis, and risk assessment to refine technology selection under evolving regulatory and disposal landscapes.

FINAL RECOMMENDATIONS

Based on the comparative evaluation of vitrification, grouting, and fluidized bed steam reforming, the recommended path forward is a technology selection framework grounded in waste characteristics, required performance duration, regulatory alignment, and operational risk tolerance.

For high-activity and long-lived waste streams requiring geologic repository durability, vitrification remains the most technically defensible option. Its demonstrated application at the Hanford Site supports its suitability where long-term chemical stability and regulatory precedent are paramount. For low-activity waste streams compatible with engineered near-surface disposal, grout-based immobilization offers a cost-effective and operationally mature solution. Implementation at Savannah River Site demonstrates that when disposal pathways are well-defined, cementitious stabilization can achieve regulatory compliance with lower implementation complexity. For chemically complex or reactive waste streams, fluidized bed steam reforming provides a viable alternative. Experience at the Idaho National Laboratory Integrated Waste Treatment Unit highlights both the potential advantages and the need for disciplined operational readiness planning.

Accordingly, no single treatment technology should be universally described. Instead, DOE waste management strategy should continue to apply a tiered, performance-based selection approach that integrates long-term disposal constraints, lifecycle cost considerations, and implementation risk. Decisions must remain anchored in defensible performance assessments

and realistic assumptions about disposal availability, recognizing that repository capacity and regulatory pathways will continue to shape the boundary conditions for treatment selection.

REFERENCES CITED

Abbotts, J., & Weems, C. (2006). Glass wars: The Hanford Tank Wastes and Public Participation. Federal Facilities Environmental Journal, 17(1), 67–77. https://doi.org/10.1002/ffej.20082

Alternatives for Treating and Disposing of High-Level Waste Could Save Billions of Dollars and Reduce Certain Risks (GAO-24-106989). Government Accountability Office. (2024, September). https://www.gao.gov/assets/gao-24-106989.pdf

Atomic Energy Act and Related Legislation. (2026). Energy.gov. https://www.energy.gov/ehss/atomic-energy-act-and-related-legislation

Bates, W., Herman, D., Langton, C., McCabe, D., Ramsey, W., & Stone, M. (2023). Follow-on Report of Analysis of Approaches to Supplemental Treatment of Low–Activity Waste at the Hanford Nuclear Reservation (Volumes I & II). OSTI OAI (U.S. Department of Energy Office of Scientific and Technical Information), Volumes I & II. https://doi.org/10.2172/1909002

Comprehensive Environmental Response, Compensation, and Liability Act, 42 U.S.C. § 9601 et seq (1993). https://www.govinfo.gov/content/pkg/USCODE-2023-title42/pdf/USCODE-2023-title42-chap103-subchapI-sec9601.pdf

DOE/EIS-0200: Final Programmatic Environmental Impact Statement (June 1997). (1997, June). Energy.gov. http://www.energy.gov/nepa/articles/doeeis-0200-final-programmatic-environmental-impact-statement-june-1997

DOE/EIS-0391: Final Environmental Impact Statement (November 2012). (2012, November). Energy.gov. http://www.energy.gov/nepa/articles/doeeis-0391-final-environmental-impact-statement-november-2012

Feng, X., P.R. Hrma, & J.H. Jr. Westsik. (1996). Glass optimization for vitrification of Hanford Site low-level tank waste. OSTI OAI (U.S. Department of Energy Office of Scientific and Technical Information). https://doi.org/10.2172/219300

Final Review of the Study on Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation. (2020). National Academies Press. https://doi.org/10.17226/25710

Fow, C. L., Mitchell, D. H., Treat, R. L., & Hymas, C. R. (1987). Pilot-scale grout production test with a simulated low-level waste. OSTI OAI (U.S. Department of Energy Office of Scientific and Technical Information). https://doi.org/10.2172/6378199

Hanford Waste Vitrification Plant Foreign Alternatives Feasibility Study (DOE/RL-90-09). (1990). U.S. Department of Energy.

Herbst, A. K., Marshall, D. W., & McCray, J. A. (1998, February 1). Idaho chemical processing plant low-activity waste grout stabilization development program FY-97 status report. (Technical Report) | OSTI.GOV. https://www.osti.gov/biblio/650159

Immobilizing nuclear waste: Status and Future Developments in Glass and Ceramic Waste Forms. (2024, October 30). The American Ceramic Society. https://ceramics.org/ceramic-tech-today/immobilizing-nuclear-waste-status-and-future-developments-in-glass-and-ceramic-waste-forms/

Jantzen, C. M., Lorier, T. H., Marra, J. C., & Pareizs, J. M. (2006, February). Durability Testing of Fluidized Bed Steam Reforming (FSBR) Waste Forms. Waste Management 2006 Conference, Tucson, AZ (USA). https://archivedproceedings.econference.io/wmsym/2006/pdfs/6373.pdf

Kaplan, D, & Thong Hang, T (2007). ESTIMATED DURATION OF THE SUBSURFACE REDUCTION ENVIRONMENT PRODUCED BY THE SALTSTONE DISPOSAL FACILITY ON THE SAVANNAH RIVER SITE.

Laws and Regulations - Hazardous Waste | South Carolina Department of Environmental Services. (2025). Sc.gov. https://des.sc.gov/programs/bureau-land-waste-management/hazardous-waste/laws-and-regulations-hazardous-waste

Langton, C., & Hill, K. A. (2024). Alternative Hanford ETF Grout Evaluation Report. In Osti.gov. http://www.osti.gov/servlets/purl/2477623

Lorier, T. H., & Langton, C. A. (2019). Review of Cementitious Materials Development and Applications that have Supported DOE-EM Missions: Waste Treatment, Conditioning, Containment Structures, Tank Closures, Facility Decommissioning, Environmental Restoration, and Structural Assessments. OSTI OAI (U.S. Department of Energy Office of Scientific and Technical Information). https://doi.org/10.2172/1527156

Luhar, I., Luhar, S., Abdullah, M. M. A. B., Nabiałek, M., Sandu, A. V., Szmidla, J., Jurczyńska, A., Razak, R. A., Aziz, I. H. A., Jamil, N. H., & Deraman, L. M. (2021). Assessment of the Suitability of Ceramic Waste in Geopolymer Composites: An Appraisal. Materials, 14(12), 3279. https://doi.org/10.3390/ma14123279

Mason, J. B., Mckibbin, J., Ryan, K., & Schmoker, D. (2003, February). Steam Reforming Technology for Denitration and Immobilization and Immobilization of DOE Tank Wastes. Waste Management 2003 Conference, Tucson, AZ. https://archivedproceedings.econference.io/wmsym/2003/pdfs/302.pdf

Mason, J., Wolf, K., Ryan, K., Roesener, S., Cowen, M., Schmoker, D., Bacala, P., & Landman, B. (2006). Steam Reforming Application for Treatment of DOE Sodium Bearing Tank Wastes at Idaho National Laboratory for Idaho Cleanup Project. Waste Management Conference 2006, Tucson, AZ. https://inldigitallibrary.inl.gov/sites/sti/sti/3303727.pdf

McDaniel, E. W. (1987). Grouting as a Waste Immobilization/Disposal Method. Waste Management for the Energy Industries Conference., Grand Rapids, ND (USA).

Neill, R H, Channell, J K, Chaturvedi, L, Little, M S, Rehfeldt, K, & Spiegler, P (1983). Evaluation of the suitability of the WIPP site.

Nuclear Waste Policy Act, 42 U.S.C. §10101 et seq. (1982). https://www.govinfo.gov/app/details/CREC-1998-01-29/CREC-1998-01-29-pt1-PgS219

Olson, A. L., Soelberg, N. R., Marshall, D. W., & Anderson, G. L. (2005, February). Mineralizing, Steam Reforming Treatment of Hanford Low-Activity Waste. Waste Management Conference 2005, Tucson, AZ. https://inldigitallibrary.inl.gov/sites/STI/STI/3169858.pdf

Resource Conservation and Recovery Act, 40 C.F.R. § 260.1 (1986). https://www.ecfr.gov/current/title-40/chapter-I/subchapter-I/part-260

Ricciotti, L., Occhicone, A., Ferone, C., Cioffi, R., Tarallo, O., & Roviello, G. (2022). Development of Geopolymer-Based Materials with Ceramic Waste for Artistic and Restoration Applications. Materials, 15(23), 8600. https://doi.org/10.3390/ma15238600

Ryan, K., Mason, B., Wolf, K., & Olson, A. (2007, February). Steam Reforming Technology Demonstration Program for Treatment of DOE Sodium Bearing Tank Wastes at Idaho National Laboratory. Waste Management 2007 Conference, Tucson, AZ (USA). https://archivedproceedings.econference.io/wmsym/2007/pdfs/7495.pdf

Sanito, R. C., Bernuy-Zumaeta, M., You, S.-J., & Wang, Y.-F. (2022). A review on vitrification technologies of hazardous waste. Journal of Environmental Management, 316, 115243. https://doi.org/10.1016/j.jenvman.2022.115243

Simpson, E. (2024, November 26). Idaho Facility Continues Progress Treating Waste, Surpasses EM 2024 Priority. Energy.gov. https://www.energy.gov/em/articles/idaho-facility-continues-progress-treating-waste-surpasses-em-2024-priority

Song, Y., Lu, X., Wang, K., Ryan, J. V., Smedskjaer, M. M., Vienna, J. D., & Mathieu Bauchy. (2024). Unveiling the effect of composition on nuclear waste immobilization glasses' durability by nonparametric machine learning. Npj Materials Degradation, 8(1). https://doi.org/10.1038/s41529-024-00458-6

The Atomic Energy Act of 1954, 42 U.S.C § 2011-2021 (2024). https://www.govinfo.gov/content/pkg/COMPS-1630/pdf/COMPS-1630.pdf

United States Government Accountability Office. (2018). Nuclear Waste: Uncertainties and Questions about Costs and Risks Persist with DOE's Tank Waste Cleanup Strategy at Hanford. Createspace Independent Publishing Platform.

U. S. Department of Energy. (2024) Hanford Tank Waste. [Fact Sheet]. https://www.hanford.gov/files.cfm/Tank_Farm_Overview_Fact_Sheet.pdf

Wakeley, L., McDaniel, E., & Ernzen, J. (1991). Grout for Closure of Waste-Disposal Vaults at the U.S. DOE Hanford Site. International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Istanbul, Turkey. https://inis.iaea.org/records/epxcn-21q52

Wilhite, E L (1986). Waste salt disposal at the Savannah River Plant.

Wilhite, E. L., Langton, C. A., & Sturm, H. F. (1989, April 27). *Saltstone Processing Startup at the Savannah River Plant*. DOE Low-Level Waste Management Conference, Denver, Colorado. https://www.osti.gov/servlets/purl/6305630

WIPP Facility Work Plan for Solid Waste Management Units. (2002). Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/924488