

Design Factors and Scale-Up Considerations for Commercial-Scale Sintering System of Dispersible Radioactive Waste: A Review of Existing Studies

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1. Introduction

Nuclear facilities generate Low and Intermediate Level radioactive Waste (LILW) in heterogeneous forms. Dispersible waste poses an elevated risk of airborne contamination and re-suspension during handling, transport, and interim storage. Consequently, dispersible streams must be rendered non-dispersible via solidification/fixation or equivalent immobilization prior to disposal.

Disposal acceptance criteria further constrain the final package and waste form by limiting free liquid, requiring package integrity during handling, and demanding verification of mechanical and chemical durability. These requirements translate into engineering design drivers across the processing line: robust moisture control and dust confinement in preprocessing, reproducible green-body forming; and a qualified thermal history that yields a dense monolithic waste form with predictable performance under repository conditions.

Pressureless sintering provides a practical thermal route for particulate feeds: waste powders are blended with additives, compacted into a green body, and densified in a furnace under a programmed thermal cycle. Relative to cementation, sintered glass-ceramic waste forms can enable higher waste loading, lower porosity, and meaningful volume reduction. However, moving from laboratory demonstrations to commercial operation requires an explicit scale-up strategy for confinement-grade material handling and nuclear-grade off-gas control, together with a Quality Assurance (QA) and Quality Control (QC) framework that links process variables to acceptance performance.

2. Sintering and solidification technology for dispersible radioactive waste

This section summarizes representative studies that are directly relevant to immobilization of dispersible radioactive wastes. The focus is on technical themes that control commercial feasibility: matrix selection, densification route, waste-stream compatibility, and process safety provisions such as dust control and off-gas capture.

2.1. Korea Atomic Energy Research Institute (KAERI)

KAERI has developed a pressureless sintering approach based on glass-ceramic composite matrices for oxide-rich dispersible wastes, including uranium-bearing particulate waste derived from spent uranium catalyst treatment. A key scale-up result is the experimental fabrication of large disk-type sintered bodies suitable for packing in a 200 L drum, demonstrating that large monoliths can be manufactured while maintaining tolerable anisotropic deformation during firing.

In the KAERI study, green bodies were prepared at a compaction pressure of 60 MPa and sintered at high temperature. Regardless of form and size, the sintered bodies exhibited high isotropic shrinkage with an average anisotropy rate of 1.6% and an average shrinkage rate of ~37.4%. These quantified shrinkage characteristics provide a practical basis for commercial mold design, furnace load planning, and crack-mitigation strategy [1].

2.2. Korea Advanced Institute of Science and Technology (KAIST)

KAIST has demonstrated an alternative low-temperature consolidation pathway for a volatile radionuclide surrogate case: iodine immobilization in iodosodalite. Cold sintering is a pressure-assisted, transient-liquid-phase process performed at substantially lower temperatures than conventional ceramic processing. In the KAIST work, consolidation at 300°C achieved high iodine retention while producing a dense monolith without additional glass or binder matrices.

The resulting cold-sintered iodosodalite exhibited a micro-hardness of 3.9 ± 0.1 GPa and compressive strength of 198 ± 11 MPa, indicating that low-temperature processing can still produce mechanically robust forms. A seven-day product consistency test reported iodine leaching rates on the order of 10^{-4} g·m⁻²·d⁻¹. For commercial sintering-system design, this study supports a modular technology envelope: high-temperature pressureless sintering for oxide-rich particulates and lower-temperature pressure-assisted consolidation options for waste streams with volatility constraints [2].

2.3. Korea Hydro & Nuclear Power (KHNP)

From an operator and decommissioning implementer perspective, KHNP's priorities emphasize field deployability: stable throughput, remote/automated operations to support ALARA, and integration with packaging logistics and documentation. For sintering-based immobilization, KHNP-relevant technical themes include modular processing trains, maintainability under radiological controls, and qualification pathways that demonstrate compliance with repository acceptance criteria using representative waste streams and controlled operating envelopes.

2.4. Sandia National Laboratories (SNL)

SNL has contributed to iodine waste form development through low-sintering-temperature glass waste forms that sequester iodine captured on adsorbents. The patented approach captures iodine as an iodine-loaded material, mixes it with powdered frits of low-sintering-temperature glass, and sinters the mixture at relatively low temperatures to form a durable glassy monolith.

A key design insight for off-gas and materials selection is the deliberate use of sintering temperatures around 500°C to mitigate iodine volatility while still achieving consolidation. The patent reports the waste form can contain up to ~60 wt% AgI, and identifies a preferred glass composition containing oxides of boron, bismuth, and zinc. For dispersible waste system design, the SNL approach highlights how temperature windows and matrix chemistry can be engineered to control volatility and leach resistance, with direct implications for furnace design, off-gas treatment sizing, and qualification testing [3].

2.5. Idaho National Laboratory (INL)

INL and broader nuclear R&D programs have evaluated advanced sintering routes, particularly spark plasma sintering (SPS), for rapid densification of powder compacts and net/near-net shape processing. As a representative public summary of SPS practice in nuclear technology, the NUGENIA+ SPARK project describes SPS as a technique that passes a high current through a die and powder compact during pressing, enabling rapid sintering within minutes and potentially combining pressing and sintering into a single step.

The NUGENIA+ SPARK summary reports SPS processing examples for UO₂ in controlled atmospheres, with fast heating/cooling rates and uniaxial pressure around 70 MPa. It also highlights scale-up-relevant constraints such as reacted surface layers from graphite tooling and the importance of controlling oxygen-to-metal ratio and microstructure. For commercial pressureless sintering systems, the SPS literature provides useful analogs for compaction integrity, tooling material selection, and the need for qualification of atmosphere and thermal histories even when the

commercial route ultimately uses conventional furnaces instead of SPS [4].

3. Key design factors for commercial-scale pressureless sintering system

Commercial deployment of a pressureless sintering line for dispersible radioactive waste should be treated as an integrated confinement and qualification system, not a stand-alone furnace. From a Waste Acceptance Criteria (WAC) standpoint, the line must be anchored to batch-verifiable checks: conversion to a non-dispersible waste form, strict control of free liquid, and demonstrated mechanical integrity and chemical durability. These requirements directly drive plant-level choices such as fully enclosed powder handling, reliable moisture management, and repeatable densification conditions that consistently yield a monolithic product.

The first scale-up bottleneck is feed conditioning, because dispersible wastes are heterogeneous and may be abrasive. A commercial line should define a feed specification envelope and include preprocessing to meet it, such as controlled top-size conditioning. Because dust generation is inherent, size reduction and transfer must be executed in sealed interfaces under negative pressure with local exhaust and filtration, alongside contamination control features such as segregated handling, cleanable contact surfaces, and wear-resistant liners to maintain stable sintering response.

Drying, blending, and forming then set product uniformity and crack risk. Forced-convection rack-type drying with programmable temperature control is preferred to minimize entrainment and to match daily throughput, with drum-to-tray transfer performed inside sealed, negatively pressurized enclosures. Blending must deliver batch-level homogeneity while minimizing dust, with controlled additive dosing and sampling provisions because chemistry strongly affects shrinkage and densification. Compaction is the primary lever for green density control and handling robustness; commercial concepts typically target stable, automated pressing and geometry that supports furnace uniformity and efficient drum packing.

At the commercial scale, the dominant technical risks shift to thermal uniformity, transfer operability, and off-gas licensing. The furnace must be specified and qualified for temperature capability and uniformity under the intended load using thermocouple mapping, resulting in a defensible operating envelope incorporated into QA. Conveyance and transfer points should be treated as confinement nodes. Finally, as summarized in Table I, the off-gas system must meet nuclear-grade requirements, including particle filtration and gas purification. It should be sized for facility airflow and designed to avoid condensation and dead zones, with provisions for safe change-out and secondary-waste management.

Table I: Design factor considerations for commercial-scale sintering system

Equipment	Specifications
Pulverizer (Pre-treatment)	Target after pulverization: particle size ≤ 0.2 mm
Drying Unit (Pre-treatment)	Type: Rack-type drying oven Capacity: 400 L
Mixer	Type: High-shear mixer (Super mixer) Capacity: 100 L (batch)
Compaction/ Forming Unit	Type: Piston press or roll compactor Compact geometry: 28 cm \times 8 cm (t) (fan-shaped)
Sintering Furnace	Maximum operating temperature: $\sim 1200^{\circ}\text{C}$ Controls: PID controller, includes temperature profile program
Air Cleaning System	Treatment capacity: < 1500 CFM (may vary depending on operating space) Configuration: pre-filters (bag filter, cyclone, metal filter), HEPA filter, adsorber

4. Conclusion

This study provides an in-depth review of domestic and international sintering technologies for the safe disposal of dispersible radioactive waste and derives key design factors for establishing a commercial-scale immobilization system. Analysis of existing literature and technical reports confirmed that sintering technology offers significant volume reduction and superior physical and chemical stability compared to conventional cementation methods. Specifically, anisotropic deformation control technology for large-scale sintered bodies [1] and non-volatile immobilization techniques are critical design considerations that must be integrated into system design. The forming pressure, sintering temperature, and radionuclide immobilization mechanisms established through this technical review will serve as the essential framework for maximizing the sequestration performance of future commercial-scale equipment.

Engineering designs that ensure thermal and physical homogeneity during large-capacity processing while minimizing environmental loads are indispensable for successful commercial-scale-up. The sector-shaped green body structure and 200L drum packing optimization strategy proposed in this research provide practical solutions for maximizing disposal space efficiency. Additionally, the integrated design of off-gas treatment and air purification systems complying with nuclear technical standards is required to manage pollutants generated during large-scale operations. Future work should focus on verifying the validity of

the design factors presented in this study through pilot-scale demonstrations using actual waste streams.

Concurrently, subsequent research must address the definition of a robust operating envelope and the establishment of a rigorous QA/QC framework for the full-scale commercialization phase.

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