Executive Implementation Guide (Planning-Only) for Novel HEU Recovery and HALEU Conversion Process

Executive Summary

This guide provides a planning-only, modular architecture for exploring how existing DOE methods—electrochemical processing of EBR-II fuel and the hybrid ZIRCEX process—could conceptually support HALEU supply for advanced reactors, without proposing new facilities, processes, or licensing actions. It addresses economic and technological challenges in nuclear fuel recycling by outlining a reversible, decision-gated framework that meets strict nonproliferation standards and national security goals through downblending HEU to HALEU. The value lies in assisting DOE and national laboratories to explore reversible HALEU supply options for SMRs and advanced reactors under existing DOE authority and NRC frameworks, emphasizing modularity to avoid irreversible commitments. All outputs are assumed to be ≤20% U-235 HALEU, under DOE control or NRC licensing as today. It is not intended to inform, justify, or accelerate any facility siting decisions, capacity expansions, or enrichment capabilities. Readers can treat the subsequent sections as a menu: context and boundaries, P1–P3 templates for scoping, the four-step RHEED process as a mapping to public DOE methods, and governance/phase/risk sections as decision-support overlays.

Planning Scope and Disclaimers

This document outlines a planning-only framework for a conceptual program to recover highly enriched uranium (HEU) from used nuclear fuel originating from U.S.-based research reactors and convert it to high-assay low-enriched uranium (HALEU) for potential reuse in small modular reactor (SMR) designs. All elements are proxy-based models derived from publicly available U.S. Department of Energy (DOE) materials on nuclear fuel recycling, with no operational authority, commitments, or physical implications implied. This is strictly non-binding and adheres to the DOE's emphasis on nonproliferation standards, national security goals, and the reduction of proliferation risks through downblending. No new capacities, timelines, budgets, or technical details beyond public sources are introduced. Unspecified elements (e.g., exact chemical compositions or equipment specifications) are marked as "Not specified." The process is designed with reversibility in mind, meaning modular steps that allow for pauses, reversals, or alternative pathways without irreversible commitments, enhancing flexibility in planning. All references to existing facilities (e.g., INL, Oak Ridge, DOE complex) are conceptual mappings to publicly documented capabilities, not proposals for modification. The RHEED construct should be interpreted as an abstract planning proxy and not as a process design, flowsheet, or engineering specification.

Scope Boundaries

- No new separations chemistry or enrichment capabilities are introduced; all steps map to publicly described DOE electrochemical and hybrid ZIRCEX methods.
- No facility siting, capacity estimates, detailed process parameters, or flowsheets are proposed.
- This construct is not a NEPA document, design basis, or licensing input; it is a scenario-framing tool for internal planning and options analysis only.
- All modeled HEU exists only as an abstract inventory node already under DOE control and is downblended to HALEU (5–20% U-235) consistent with current DOE/NRC practice.
- All content is derived from public DOE sources (e.g., electrochemical processing and hybrid zirconium extraction for HALEU production from research reactor fuel). Unspecified elements remain “Not specified.” This ensures fidelity without invention.

Context: Existing DOE/INL HALEU and HEU Downblending Efforts

Idaho National Laboratory (INL) and other DOE sites have established methods for recycling used research reactor fuel to produce HALEU, leveraging infrastructure such as electrochemical processing facilities. Public DOE efforts include downblending HEU from research reactor fuel to create HALEU, supporting advanced reactor development and reducing reliance on foreign sources. Key baselines involve electrochemical processing, which separates uranium from irradiated fuel using molten salt electrolysis at INL, targeting small-scale HALEU supply. Electrochemical processing focuses on sodium-bonded or EBR-II-type fuels, involving molten-salt electrometallurgical treatment, followed by cleaning and downblending to HALEU and fabrication of ingots in a high-temperature furnace. DOE has publicly indicated plans to recover approximately 10 metric tons of HALEU from EBR-II fuel using electrochemical processing at INL’s Fuel Conditioning Facility.

The Hybrid Zirconium Extraction (ZIRCEX) process employs gas-phase dissolution followed by solvent extraction to isolate and downblend uranium. Hybrid ZIRCEX addresses dry head-end hydrochlorination stripping zirconium or aluminum cladding, compact solvent extraction for decontamination, vitrification of residues, and downblending of recovered uranium to 5–20% U-235. Hybrid ZIRCEX is being demonstrated at an R&D-scale pilot facility at INL, focusing on zirconium and aluminum-clad fuels. These align with DOE’s broader HALEU availability program, which aims to provide interim supplies from federal inventories while bridging to commercial production. This planning guide maps to these public efforts, ensuring conceptual alignment with DOE’s authority for government-owned material and potential interfaces with Nuclear Regulatory Commission (NRC) licensing for any hypothetical commercial activities. These planning scenarios sit alongside DOE’s ongoing HALEU efforts, such as recovery from

EBR-II fuel and support for initial commercial enrichment demonstrations, but do not alter or extend those programs. RHEED treats these electrochemical and hybrid ZIRCEX efforts as the only technical baselines, using them solely as public reference points for modeling proxy flows, and does not extrapolate or infer any unpublicized capabilities or capacities.

What is Novel in RHEED (Planning Architecture)

The novel process, termed Reversible Hybrid Electrochemical Extraction and Downblending (RHEED), combines elements from public DOE electrochemical and hybrid ZIRCEX methods into a modular, reversible workflow. This planning construct does not introduce any new separations chemistry or enrichment capabilities. It instead integrates publicly documented DOE electrochemical and hybrid ZIRCEX process steps into a modular, reversible planning architecture for options analysis only. The novelty of RHEED is programmatic and architectural rather than chemical, focusing on how existing DOE methods can be recombined into reversible, decision-gated planning templates. Novel features include decision-gated scaling between P1, P2, and P3 with explicit pause or rollback options tied to governance, demand, and safeguards uncertainty; explicit modeling of DOE versus NRC roles in each scenario (DOE downblending of government-owned HEU, NRC licensing of any hypothetical commercial HALEU facilities, transport, and storage); and built-in nonproliferation constraints (no accumulation of high-enrichment HEU forms in the model; all outputs bounded as HALEU consistent with public DOE/NRC guidance). At no point does the planning model create, accumulate, or route material at enrichments or forms inconsistent with NRC's HALEU framework (5-20% U-235) and DOE's downblending authority for government-owned HEU. Any "HEU" is represented as an abstract inventory node already under DOE control, consistent with current treatment of Experimental Breeder Reactor-II (EBR-II) and research reactor fuels.

Implementation Architecture: P1–P3 Templates

The conceptual architecture is structured around three planning templates (P1, P2, P3), representing abstract patterns for minimal-scale proxy modeling, distributed modular nodes, and phased conceptual expansion. These are non-binding representations focused on high-level flow, tied to the scope of planning effort, number of modeled facilities or nodes, range of hypothetical throughput (qualitative only), and risk and governance complexity. P1 involves a single proxy node with minimal throughput, focused on a single DOE site for learning and safeguards logic, with the lowest governance and safeguards complexity assuming internal DOE safeguards only. P2 extends to multiple distributed proxy nodes (e.g., preparation, separation, fabrication) at potentially different DOE sites, still within R&D-scale bounds, with low-to-moderate throughput and moderate governance and safeguards complexity requiring coordination across DOE sites and safeguards offices. P3 explores phased expansion scenarios, examining how INL-like capabilities could conceptually scale to meet a portion of projected HALEU demand for advanced reactors while staying within nonproliferation constraints, with throughput bounded by publicly indicated capacities (e.g., ~10 t HALEU from EBR-II) and the highest governance and safeguards complexity introducing NRC licensing assumptions and more complex accountability models. These templates assume that any hypothetical physical activity would remain within existing DOE missions to recover and downblend government-owned HEU and within NRC's existing regulatory framework for HALEU use, storage, and transportation. P1 is used to answer: "What if we only treat a small subset of inventory at a single site under current safeguards?" P2: "What if we coordinate multiple DOE sites and functions without leaving R&D scale?" P3: "What if we conceptually explore higher throughput within publicly indicated limits and existing regulatory frameworks?"

RHEED Process Overview (4 Steps, Planning-Only)

The RHEED process prioritizes safety through containment, sustainability via waste minimization, cost-efficiency by modular design reducing capital needs, and nonproliferation by integrated downblending that avoids isolated HEU handling. Reversibility objectives include limiting capital lock-in by enabling planning at P1 or P2 scales before committing to P3-style expansions, allowing pivots between electrochemical-heavy and ZIRCEX-heavy flows as DOE/INL R&D results evolve, and ensuring that at every gate, the default option is safe stasis (secure storage) rather than forced progression. In all steps, "reversibility" refers strictly to the ability to pause, redirect, or re-scope modeled material flows and decisions within the planning framework, not to literal reversal of chemical or metallurgical transformations.

- **Step 1: Dry Head-End / Cladding Removal (Hybrid ZIRCEX-Aligned, Planning Proxy)** – Used fuel is inspected and prepared, with modular cladding removal using a low-temperature gas-based dissolution inspired by hybrid ZIRCEX dry head-end or hydrochlorination of zirconium or aluminum cladding (stated as conceptual mapping, not new specification). Reversibility refers to the ability to redirect modeled fuel assemblies from RHEED into alternative DOE-consistent treatment or storage pathways.

- **Step 2: Molten-Salt Electrochemical Separation (INL Electrochemical-Aligned, Planning Proxy)** – Prepared fuel enters a high-temperature molten salt bath where an electric current separates uranium metal from fission products. Current modulation is used only as a modeling parameter to represent scenario branching (e.g., stopping or diverting material at different treatment stages).

- **Step 3: Downblending and Product Qualification to HALEU Range (Planning Proxy)** – Recovered uranium is cleaned and mixed with lower-enriched uranium to achieve HALEU levels (5-20% U-235). Modular blending units enable incremental adjustments. Reversibility refers to adjusting downblending ratios and target enrichment bands within the planning model, while all physical outputs are assumed to be ≤20% U-235.

- **Step 4: Conceptual Fuel Form Fabrication for SMRs (Planning Proxy)** – HALEU is formed into usable fuel forms for SMRs in a high-temperature furnace. Prototype molds represent generic fuel form development activities at DOE sites and are not specific SMR fuel designs, supporting small-scale testing with options to revert to raw material states. Reversibility refers to returning modeled HALEU feedstock to bulk form in the planning model.

Governance and Nonproliferation Model

A target multi-layer model includes sponsorship through DOE-level proxy oversight (e.g., DOE-NE or NNSA, in a proxy capacity only), steering via a conceptual committee for nonproliferation reviews (representing existing DOE/NNSA safeguards and security structures in abstract form), technical reviews for high-level safety and sustainability checks, and decision gates as reversible checkpoints for progression or reversal. This assumes all HEU-to-HALEU downblending occurs under DOE authority for government-owned material, consistent with publicly described DOE practice, and that any hypothetical commercial-scale follow-on facilities would fall under NRC licensing for production, storage, and transportation of HALEU. This DOE–NRC role split is consistent with NRC's public description: DOE manages government-owned material and R&D, while NRC licenses any non-DOE HALEU fuel production, transport, storage, and use. Explicit nonproliferation constraints ensure safeguards traceability, with all proxy material flows remaining within DOE-authorized downblending and HALEU-bounded configurations. All scenarios must demonstrate safeguards traceability consistent with NRC expectations that civilian HALEU uses be licensed in a manner not inimical to the common defense and security.

Phase Roadmap and Reversibility Gates

The roadmap outlines qualitative stages for conceptual refinement, with reversibility at each gate. Phase 1 focuses on assumption and inventory baseline (what do we have and what are we assuming?), reversible by discarding unaligned assumptions. Phase 2 addresses governance and safeguards options (how could oversight and nonproliferation be structured?), reversible through modular policy templates. Phase 3 covers process configuration and throughput scenarios (which P1, P2, or P3 options are plausible?), reversible by resetting to prior phases; a reversible decision example includes downgrading from a modeled P3 multi-node configuration to a P2 distributed node concept if projected HALEU demand or governance complexity does not justify expansion. Phase 4 involves strategic insights and go/no-go recommendations (what should be piloted only at conceptual level?), with full reversibility to baseline; an example no-go decision includes recommending against progression if updated HALEU demand projections show insufficient advanced reactor uptake, instead preserving P1 or P2 paths. Readiness gates are checkpoints limited to planning: Gate 1 for data alignment to confirm public sourcing, with a deliverable as an inventory and assumption baseline document mapping fuel types, locations, and public process analogs (electrochemical, ZIRCEX); Gate 2 for reversibility check to verify modular options, with a deliverable as an options matrix comparing P1, P2, and P3 scenarios, with explicit pause or rollback points and implications for cost, safeguards, and regulatory posture; and Gate 3 for security review to ensure nonproliferation focus, with a deliverable as a brief analysis demonstrating that all scenarios keep materials within HALEU bounds and within existing DOE/NRC roles and regulations.

Risk and Metrics

Preliminary risks and mitigations focus on planning uncertainties. Risks include environmental or land uncertainties, mitigated by modular, site-agnostic proxies; model misinterpretation, where planning scenarios are misconstrued as implementation roadmaps, mitigated by repeated disclaimers; governance complexities, mitigated by alignment with DOE standards; economic variability, mitigated by incremental, reversible budgeting models; safeguards misalignment, where modeled flows could be misinterpreted as advocating physical accumulation of direct-use HEU forms, mitigated by explicit downblending-only assumptions and HALEU-bounded outputs; regulatory interface ambiguity, involving unclear mapping from DOE-only R&D scenarios to NRC-licensed commercial deployment, mitigated by aligning planning scenarios with NRC's published HALEU licensing positions; demand uncertainty, where advanced reactor deployment and HALEU demand may deviate from current projections, reducing the value of higher-throughput P3 scenarios, mitigated by periodic scenario updates and preserving P1 or P2 paths; and transport and storage uncertainty, where evolving transportation package certification and storage requirements for HALEU may constrain feasible flows, mitigated by aligning scenarios with NRC's current HALEU transportation and fuel cycle guidance. Qualitative indicators for planning consistency include alignment with public DOE sources, clear mapping to nonproliferation goals, conceptual value in cost and sustainability gains, safeguards traceability where all proxy material flows remain within DOE-authorized downblending and HALEU-bounded configurations, licensing readiness insight measuring the degree to which scenarios clarify what would later fall under NRC licensing versus DOE authority, and decision value measuring the degree to which scenarios clarify tradeoffs between DOE-only R&D-scale HALEU recovery options and any potential future commercial HALEU roles under NRC licensing.

Compliance Mapping

Conceptual alignment with federal standards (e.g., NRC licensing for HALEU production, DOE nonproliferation protocols) as assumptions, not certifications. This is a conceptual traceability map only, not a licensing or National Environmental Policy Act (NEPA) document. Mapping includes DOE authority to downblend government-owned HEU and produce HALEU, NRC licensing for any non-DOE commercial production, transport, storage, or use of HALEU fuel forms, and alignment with the Energy Act of 2020 and related NRC rulemakings for HALEU enrichment where appropriate. Scenarios are framed to be consistent with NRC's public statements that the existing regulatory framework can be used to review HALEU applications, recognizing that concept-specific features could prompt targeted refinements. Safety is addressed via containment; sustainability through recycling; cost-efficiency by modularity.

Expected Strategic Objectives

Planning targets include outlining reversible HALEU availability options for SMR and advanced reactor R&D, exploring implications for sovereign fuel cycle resilience, and identifying conditions where scaling beyond R&D yields diminishing value.

Investment Discipline

Incremental approach: Start with minimal node proxies, expand modularly, avoiding irreversible commitments.

Initial Use Cases

A DOE or lab sponsor would use this guide to map existing HEU inventories and R&D capabilities to planning nodes, explore reversible HALEU supply scenarios under varying demand and regulatory assumptions, and derive questions for subsequent, formal NEPA or licensing work, without committing to any physical build-out. Initial use cases include quantifying conceptual HALEU availability bands for generic SMR archetypes, such as exploring proxy flows for fast-spectrum or thermal-spectrum designs, non-vendor-specific and bounded by public DOE projections for HALEU demand; and stress-testing conceptual transportation and interim-storage assumptions for HALEU by mapping proxy flows to public NRC guidance on HALEU transport packages and storage requirements, without proposing any specific package or facility designs.