Executive Implementation Guide (Planning-Only) for Novel Process to Produce Uranium Hexafluoride from Used Fuel

Executive Summary

This guide provides a planning-only, modular architecture for exploring how existing DOE methods—electrometallurgical treatment and fluoride volatility concepts—could conceptually support production of uranium hexafluoride (UF6) from used nuclear fuel, 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 safe, sustainable recovery and conversion. The value lies in assisting DOE and national laboratories to explore reversible UF6 production options for fuel cycle integration under existing DOE authority and NRC frameworks, emphasizing modularity to avoid irreversible commitments. All outputs are assumed to be in forms consistent with current DOE/NRC practice for handling UF6. 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 REFC 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 produce uranium hexafluoride (UF6) gas from used nuclear fuel. 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 controlled recovery and conversion. 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, DOE complex) are conceptual mappings to publicly documented capabilities, not proposals for modification. The REFC 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 conversion capabilities are introduced; all steps map to publicly described DOE electrometallurgical and fluoride-based 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 used fuel exists only as an abstract inventory node already under DOE control and is converted to UF6 consistent with current DOE/NRC practice.
- All content is derived from public DOE and national lab sources (e.g., electrometallurgical treatment for uranium recovery and R&D on fluoride volatility–based UF6 production from used fuel). Unspecified elements remain "Not specified." This ensures fidelity without invention.

Context: Existing DOE/INL Efforts for UF6 Production from Used Fuel

Idaho National Laboratory (INL) and other DOE sites have established methods for treating used nuclear fuel to recover uranium, which in principle can be converted to UF6 for re-enrichment or other fuel cycle uses using established uranium conversion technologies. Public DOE efforts include electrometallurgical processing to separate uranium from fission products in used fuel, supporting sustainable fuel cycles and reducing waste. Key baselines involve electrometallurgical treatment, which uses molten salt electrolysis at INL to recover uranium metal from irradiated fuel, targeting recovery for further processing. Electrometallurgical processing focuses on sodium-bonded or EBR-II-type fuels, involving anodic dissolution, electrorefining, and recovery of uranium metal, which in principle can be converted to UF6 using established uranium conversion technologies. DOE has publicly supported development of processes that could produce UF6 from used fuel, including awards to industry and laboratories for innovative conversion concepts.

Fluoride-based methods, such as fluoride volatility, treat used fuel with fluorine gas to form volatile fluorides, including UF6, for separation and recovery. Fluoride volatility addresses direct conversion of oxides or metals in used fuel to fluorides, with UF6 as a key product for enrichment. These align with DOE's broader fuel cycle program, which aims to advance recycling technologies that meet nonproliferation standards while providing sustainable fuel supplies. 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 fuel cycle efforts, such as recovery from EBR-II fuel and support for UF6 process development and demonstration concepts, but do not alter or extend those programs. REFC treats these electrometallurgical and fluoride volatility 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 REFC (Planning Architecture)

The REFC framework (Reversible Electrochemical Fluorination and Conversion) combines elements from public DOE electrometallurgical and fluoride volatility methods into a modular, reversible workflow. This planning construct does not introduce any new separations chemistry or conversion capabilities. It instead integrates publicly documented DOE electrometallurgical and fluoride volatility process steps into a modular, reversible planning architecture for options analysis only. The novelty of REFC 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 treatment of government-owned used fuel, NRC licensing of any hypothetical commercial UF6 facilities, transport, and storage); and built-in nonproliferation constraints (no accumulation of direct-use or high-enrichment material forms in the model; all outputs bounded as UF6 consistent with public DOE/NRC guidance). At no point does the planning model create, accumulate, or route material at forms inconsistent with DOE's authority for used fuel treatment and NRC's framework for UF6 handling. Any "used fuel" is represented as an abstract inventory node already under DOE control, consistent with current treatment of 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, conversion) 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 UF6 demand for fuel cycles while staying within nonproliferation constraints, with throughput bounded by publicly indicated capacities 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 treat used fuel and within NRC's existing regulatory framework for UF6 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?”

REFC Process Overview (4 Steps, Planning-Only)

The REFC process prioritizes safety through containment, sustainability via waste minimization, cost-efficiency by modular design reducing capital needs, and nonproliferation by integrated conversion that avoids isolated fissile material 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 electrometallurgical-heavy and fluoride-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: Fuel Preparation (Electrometallurgical-Aligned, Planning Proxy)** – Used fuel is inspected and prepared, with modular decladding using methods inspired by dry head-end processes (stated as conceptual mapping, not new specification). Reversibility refers to the ability to redirect modeled fuel assemblies from REFC into alternative DOE-consistent treatment or storage pathways.

- **Step 2: Uranium Recovery (Electrometallurgical-Aligned, Planning Proxy)** – Prepared fuel enters a high-temperature molten salt bath where an electric current separates uranium 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: Fluorination (Fluoride Volatility-Aligned, Planning Proxy)** – Recovered uranium is represented as being reacted with fluorinating agents to form UF6 gas in the model, conceptually mapping to dry fluoride volatility and related R&D. Modular reaction units enable incremental adjustments in the planning model. Reversibility refers to adjusting assumed reaction parameters and product routing within the planning model; all modeled gaseous outputs are treated as UF6 consistent with current practice for UF6 handling.

- **Step 4: Product Qualification and Storage (Planning Proxy)** – UF6 is condensed and qualified for storage or transport. This represents generic handling activities at DOE sites and is not specific to commercial uses, supporting small-scale testing with options to revert to intermediate states. Reversibility refers to returning modeled UF6 feedstock to prior forms 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 used fuel treatment 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 UF6. 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 UF6 fuel production, transport, storage, and use. Explicit nonproliferation constraints ensure safeguards traceability, with all proxy material flows remaining within DOE-authorized treatment and UF6-bounded configurations. All scenarios must demonstrate safeguards traceability consistent with NRC expectations that civilian UF6 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 UF6 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 UF6 demand projections show insufficient fuel cycle 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 (electrometallurgical, fluoride volatility); 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 UF6 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 forms, mitigated by explicit conversion-only assumptions and UF6-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 UF6 licensing positions; demand uncertainty, where fuel cycle deployment and UF6 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 UF6 may constrain feasible flows, mitigated by aligning scenarios with NRC's current UF6 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 treatment and UF6-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 UF6 production options and any potential future commercial UF6 roles under NRC licensing.

Compliance Mapping

Conceptual alignment with federal standards (e.g., NRC licensing for UF6 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 treat used fuel and, where applicable, convert recovered uranium into UF6 under DOE missions, NRC licensing for any non-DOE commercial production, transport, storage, or use of UF6, and alignment with the Energy Act of 2020 and related NRC rulemakings for fuel cycle activities where appropriate. Scenarios are framed to be consistent with NRC's public statements that the existing regulatory framework can be used to review UF6 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 UF6 production options for fuel cycle 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 used fuel inventories and R&D capabilities to planning nodes, explore reversible UF6 production 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 UF6 availability bands for generic fuel cycle archetypes, such as exploring proxy flows for enrichment or fabrication designs, non-vendor-specific and bounded by public DOE projections for UF6 demand; and stress-testing conceptual transportation and interim-storage assumptions for UF6 by mapping proxy flows to public NRC guidance on UF6 transport packages and storage requirements, without proposing any specific package or facility designs.