

TRILATERAL ENERGY SECURITY COMMITTEE

Uranium Processing Supply Chain Security: A Framework for Trilateral Investment Coordination

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Executive Summary

The expansion of nuclear power is accelerating globally, driven by increased energy demand projections, decarbonization policies, and energy security concerns, yet fuel-cycle security remains misaligned with these deployment ambitions. While uranium mining is geographically dispersed across Kazakhstan, Canada, Australia, Namibia, and other nations, midstream conversion and enrichment operations remain highly concentrated, creating acute dependencies that increase exposure to geopolitical and supply chain security risk.

For the U.S., Japan, and South Korea (the "Triad"), the challenge is uniquely shared. The U.S. relies on imports for approximately two-thirds of its uranium needs, which is expected to increase even further. Japan imports 100% of its natural uranium and operates limited domestic enrichment capacity at Rokkasho, and South Korea imports 100% of its uranium and enriched fuel, with nuclear energy accounting for 31% of its electricity generation. Enrichment and conversion capacity remain highly concentrated among a small number of suppliers, with Russia maintaining a dominant share of around 40%. For the high-assay low-enriched uranium (HALEU) required by advanced reactors, Russia and China are currently the only commercial suppliers.

This report utilizes a stage-based structural analysis framework to identify where coordinated intervention is both feasible and necessary. The results are clear: upstream activities are constrained by geology and cannot be relocated, while downstream capabilities are relatively resilient but dependent on upstream inputs. Midstream processing stages, particularly conversion, enrichment, and HALEU production, represent the only segment where high vulnerability intersects with high feasibility of coordinated investment.

A coordinated trilateral strategy—anchored by the U.S., Japan, and South Korea but extended across a broader network of allied partner economies—can materially shift the structure of the uranium fuel cycle. By aligning capital investment, aggregating demand, and distributing production across partner economies, the Triad can establish an independent fuel-cycle architecture capable of meeting its own requirements without reliance on concentrated and/or non-allied supply. While the scale of required coordinated investment is significant, it is both tractable and necessary for the Triad's structural independence in nuclear fuel services. However, the window for proactive coordination is narrowing as demand accelerates and geopolitical fragmentation deepens.

Introduction

As of April 2026, approximately 440 nuclear reactors with a 401GWe capacity operate across 31 countries (World Nuclear Association, 2026a). An additional 86 GW is under construction, with 39 GW in China alone. The Triad makes up almost 40% of global nuclear capacity, with the U.S. operating 97 GWe of capacity, Japan maintaining 32 GW—and is working to rapidly restart reactors that were shut down after the meltdown in Fukushima—and South Korea currently operating a 26 GWe capacity—which accounted for 32% of its electricity in 2024 (World Nuclear Association, 2026a).

Yet this nuclear leadership rests on a precarious foundation: significant dependence on imported nuclear fuel services and highly concentrated midstream processing controlled by geopolitical competitors. Russia alone controls roughly 40-43% of global enrichment capacity (Haneklaus et al., 2025). The combination of long project lead times, technological barriers, non-proliferation constraints, and decades of underinvestment has created structural vulnerabilities across the nuclear fuel cycle.

Without coordinated trilateral investment—alongside collaboration with other allied nations—across conversion, enrichment, and HALEU production—the U.S., Japan, and South Korea will remain structurally exposed to fuel-cycle disruption despite expanding nuclear deployment. The uranium fuel cycle presents clear priority intervention points where coordinated trilateral action can most effectively reduce structural supply chain vulnerabilities.

Strategic and Policy Context

The global nuclear fuel cycle is increasingly shaped by geopolitical concentration and coordinated policy responses. Recent geopolitical developments have further exposed these structural vulnerabilities. In May 2024, the U.S. enacted the Prohibiting Russian Uranium Imports Act, which phases out imports of Russian enriched uranium through 2040 (U.S. NRC, 2024). Russia subsequently introduced reciprocal export restrictions (Lyrchikova, 2024). U.S. utilities have historically sourced roughly one-quarter of their enriched uranium requirements from Russia, while European operators also maintain significant dependence on Russian enrichment services (Yerushalmy, 2024).

China's expanding fuel-cycle footprint introduces an additional medium-term concentration risk. China National Nuclear Corporation (CNNC) is rapidly scaling capacity to support China's large reactor construction program and growing export ambitions. China currently accounts for roughly 16% of global enrichment capacity and is continuing to expand its fuel-cycle infrastructure (World Nuclear Association, 2025).

In response to these emerging vulnerabilities, the U.S., Japan, and South Korea have begun strengthening domestic nuclear fuel capabilities through expanded policy support and industrial investment. In the U.S., the Infrastructure Investment and Jobs Act (2021), the Inflation Reduction Act (2022), and the ADVANCE Act (2024) collectively provide significant incentives for nuclear deployment, fuel security, and licensing reform (EPA, 2026). As part of this effort, the U.S. Department of Energy committed \$150 million to Centrus Energy to establish initial domestic HALEU production capacity (Dalton, 2022) and in January 2026, announced a \$2.7 billion funding program over the next 10 years to expand domestic uranium enrichment capacity which will support the production of low-enriched uranium (LEU) for existing reactors and HALEU required for next-generation reactors. As such, American Centrifuge, General Matter, and Orano Federal Services each received contracts worth approximately \$900 million (U.S. Department of Energy, 2026).

Japan has similarly repositioned nuclear energy within its Green Transformation (GX) strategy, approving reactor restarts and signaling renewed long-term reliance on nuclear power. The Japan Nuclear Fuel Limited (JNFL) Rokkasho facility provides approximately 75 tons SWU¹/year of the planned 1,050 tons SWU/year capacity from May 2013 (JNFL, 2026) and aims to expand capacity to 450 tons SWU/year by FY2028 (Japan Atomic Industrial Forum, Inc., 2025). South Korea has likewise reversed its prior nuclear phase-out policy and is focused on maintaining and gradually increasing the share of nuclear power, although it remains fully dependent on imported uranium and enrichment services.

Multilateral cooperation has accelerated alongside national policy shifts. In April 2023, Canada, France, Japan, the United Kingdom, and the U.S. launched the “Sapporo Five” initiative to diversify nuclear fuel supply chains and reduce reliance on Russian services (Natural Resources Canada, 2025). Trilateral cooperation has also deepened: the August 2023 Camp David summit committed the U.S., Japan, and South Korea to enhanced collaboration on critical minerals and energy security, and the September 2025 trilateral foreign ministerial reaffirmed joint priorities on supply chain resilience (U.S. Department of State, 2025). These policies collectively signal renewed investment but remain insufficiently implemented to fully address midstream capacity constraints.

¹ SWU means Separative Work Unit which is the standard unit measuring enrichment work.

Uranium Processing Supply Chain: Stage-by-Stage Analysis

Upstream: Exploration, Delineation, Permitting, and Extraction

Global uranium production is concentrated in a limited number of jurisdictions, led by Kazakhstan, 40% of world production, and Canada, 15% of global production via high-grade mines such as Cigar Lake and McArthur River (World Nuclear Association, 2026b). Australia (~9%), Namibia (~11%), and Uzbekistan (~7%) round out the leading producers (World Nuclear Association, 2024). A significant share of Kazakhstan's uranium output relies on Russian conversion and enrichment pathways, creating an indirect chokepoint in the fuel cycle. While uranium resources are geographically distributed, active production remains concentrated, increasing exposure to geopolitical and processing dependencies across upstream supply.

Midstream: Conversion and UF₆ Handling

Four companies control global conversion: Orano (EU, 21.3%), Rosatom (Russia, 26.5%), Cameco (Canada, 19.9%), and ConverDyn (US, 21.8%) (European Commission, n.d.). Orano's modernized Comurhex II platform was designed for 15,000 tU per year of conversion capacity, making it one of the largest Western facilities (Orano, n.d.). In the U.S., ConverDyn markets output from the Metropolis Works facility in Illinois, the country's only commercial conversion plant. The facility has a nominal capacity of about 14,000 tU UF₆ per year, representing roughly 20% of global conversion capacity (ConverDyn, n.d.). ConverDyn's Metropolis Works facility was idled from 2017 until its 2023 restart due to poor market conditions (ConverDyn, n.d.). Although the restart restored the facility, domestic capacity remains insufficient to meet total U.S. demand on its own. Even at full operation, Metropolis Works could only supply up to roughly 50% of U.S. requirements. More broadly, aggregate Western conversion capacity only modestly exceeds current U.S.-EU requirements, leaving limited surge margin in the event of supply disruption (Clean Air Task Force, 2025). As a result, conversion represents a tight but manageable constraint, provided that planned capacity expansions proceed on schedule.

Midstream: Enrichment and Advanced Processing

Enrichment remains the most acute concentration risk in the nuclear fuel cycle. Industry assessments indicate Russia controls roughly 40–43% of global enrichment capacity (27 million SWUs), giving Rosatom a dominant position in nuclear fuel services (Kim, n.d.). Urenco, a UK-Netherlands-Germany consortium, is the leading Western supplier and historically has held roughly around 29% of the global enrichment market (18 million SWUs), with major facilities in Europe and the U.S. (World Nuclear Association, 2025). Global enrichment capacity is commonly estimated in the range of ~65-70 million SWU per year, highlighting the scale of the market and the significance of Russia's market share (Hidayat,

2025). The U.S. currently has a single operating commercial-scale enrichment facility, Urenco USA in New Mexico. While additional domestic capability exists in the form of Centrus Energy’s licensed facility in Ohio, it remains at demonstration scale and does not yet provide large-scale commercial enrichment services. Because Japan and South Korea face significant political and nonproliferation constraints on developing domestic enrichment capacity, the Triad collectively depends on a limited number of facilities for enrichment services. This concentration creates a system-wide bottleneck within the uranium supply chain (The Oregon Group, 2026).

HALEU Production

HALEU represents one of the most acute emerging vulnerabilities in the advanced nuclear fuel cycle. Russia and China are currently the only HALEU producers at commercial scale, creating significant supply risk for next-generation reactors (World Nuclear Association, 2026c). The U.S. has begun rebuilding domestic capability through the Department of Energy’s HALEU Demonstration Program with Centrus Energy. Centrus delivered an initial 20 kg of HALEU in November 2023 and has since demonstrated production at an annualized rate of approximately 900 kg per year from its Piketon, Ohio cascade (Nuclear Newswire, 2025). However, projected demand far exceeds near-term supply. Department of Energy-linked estimates indicate U.S. HALEU requirements could reach ~50 metric tons per year by 2035 to support small modular and advanced reactor deployment (Department of Energy, 2024). This widening gap between demonstration-scale output and future commercial demand represents the most immediate fuel-cycle constraint for advanced reactor deployment facing next-generation nuclear deployment.

Downstream: Fabrication, Reactor Operations, and Back-End Management

The fuel fabrication segment is comparatively more diversified and remains an area of relative strength for the Triad’s industrial base. Major global suppliers include:

- Westinghouse (Cameco-Brookfield owned, Sweden, U.S., UK, Spain)
- Framatome (France, Germany)
- TVEL (Rosatom, Russia)
- Global Nuclear Fuel (GE Vernova-Hitachi)
- Mitsubishi Nuclear Fuel (Japan)
- KEPCO Nuclear Fuel (South Korea)
- CNNC (China)

Western and allied firms maintain strong technological capabilities and multiple fabrication sites across North America, Europe, and Asia. Nevertheless, fabrication security remains structurally dependent on upstream conversion and enrichment services, where market concentration is significantly higher.

The Petri map in Figure 1 illustrates the structural configuration of the uranium fuel cycle, highlighting concentration risks, existing allied capabilities, and priority intervention points for the U.S., Japan, and South Korea. While uranium ore deposits are geographically distributed and additional mining capacity exists, active production remains concentrated and slow to expand due to geological and regulatory constraints. In contrast, midstream conversion and enrichment stages exhibit both high geopolitical concentration and high complementarity potential, making them the primary targets for coordinated investment. Downstream fabrication and reactor operations remain in areas of relative strength but are structurally dependent on midstream supply security. Priority investment nodes are identified where coordinated trilateral action can most effectively reduce supply chain vulnerability.

Petri Map

Uranium Supply Chain

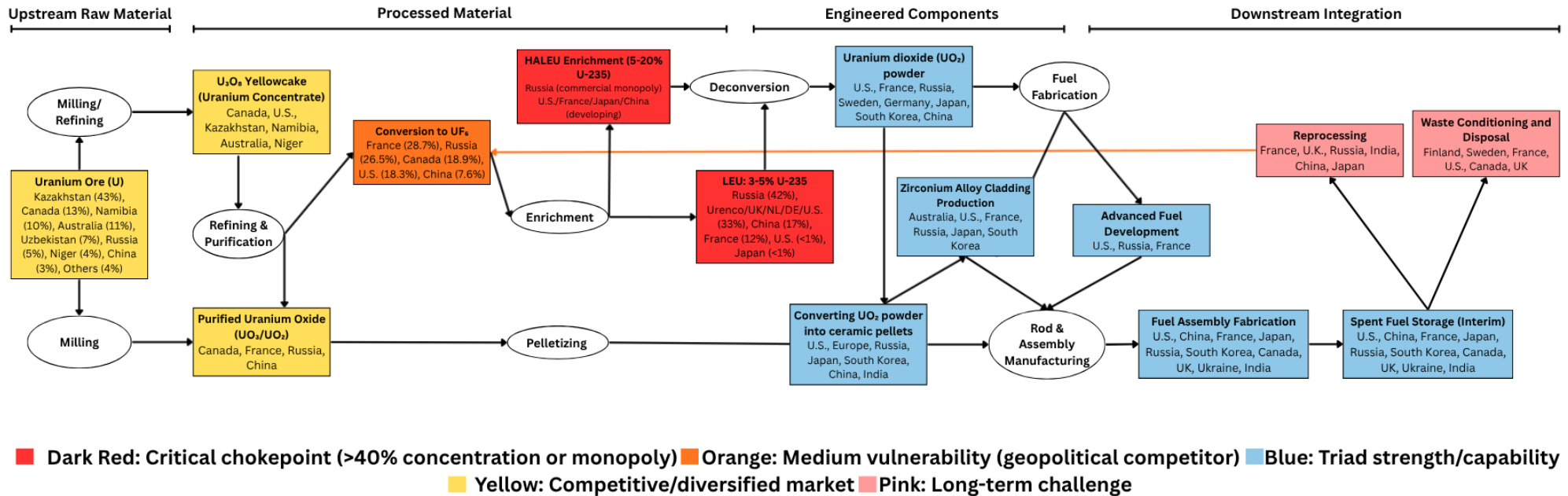


Figure 1: Uranium Petri Map

Cluster & Factor Analysis Framework of Uranium Supply Chain Stages

The uranium fuel cycle presents unique characteristics that differentiate it from other critical mineral supply chains. To systematically evaluate where trilateral coordination is structurally feasible and strategically necessary, this section applies the Cluster & Factor Analysis Framework (CFAF) to uranium supply chain stages evaluating each against eight structural factors that capture foundational prerequisites, catalytic enablers, and security-related constraints (see Appendix A for further information about the CFAF). Unlike conventional supply chain analysis, which focuses on current market conditions, the CFAF framework evaluates underlying structural constraints and opportunities, enabling identification of broad intervention points that remain robust across future market scenarios, but warrants further case-specific analyses post-identification.

Stage ID	Stage Name	Stage Type	F1	F2	F3	F4	F5	F6	F7	F8
1	Geological Survey & Exploration	Upstream	H	H	H	L	NA	NA	L	L
2a	Resource Delineation	Upstream	H	H	H	L	NA	NA	L	L
2b	Permitting & Regulatory Approval	Upstream	M	H	H	M	NA	NA	M	L
3	Extraction / Mining	Upstream	H	H	H	H	NA	NA	H	L
4	Milling & Concentration (U ₃ O ₈ / Yellowcake)	Upstream	H	H	H	H	NA	NA	H	M
5	Conversion (U ₃ O ₈ to UF ₆)	Midstream	NA	H	H	H	H	NA	H	H
6	UF ₆ Handling, Storage & Logistics	Midstream	NA	H	H	H	H	NA	H	H
7	Enrichment (LEU 3–5%)	Midstream	NA	H	H	H	H	NA	H	H
8	Enrichment (HALEU 5–20%)	Midstream	NA	H	H	H	H	NA	H	H
9	Deconversion (UF ₆ to UO ₂ or Other Forms)	Midstream	NA	H	H	H	H	NA	H	H
10	Fuel Material Production (Powder & Pellets)	Midstream	NA	H	H	H	H	NA	M	H
11	Fuel Qualification, Testing & Licensing Support	Midstream	NA	H	H	H	H	NA	H	M
12	Nuclear Material Transport & Security	Midstream	NA	H	H	H	H	NA	H	H
13	Cladding & Structural Components Production	Midstream	NA	H	H	H	H	NA	H	H
14	Component Verification & Quality Assurance	Midstream	NA	H	H	H	NA	NA	M	H
15	Fuel Fabrication (Assemblies)	Downstream	NA	H	H	H	NA	H	H	H
16	Reactor Operations	Downstream	NA	H	H	H	NA	L	H	M
17	Spent Fuel Storage (Interim)	Downstream	NA	H	H	H	NA	L	M	L
18	Waste Conditioning & Geological Disposal	Downstream	NA	H	H	H	NA	L	H	M

H	High - Strong Structural dependence; the factor is a significant enabler of action for this stage.
M	Medium - Moderate structural relevance; the factor influences the stage but requires targeted intervention.
L	Low - Limited structural relevance; the factor is a constraint or offers little leverage for this stage.
U	Unknown - Insufficient structural evidence to determine dependence.
NA	Not Applicable - The factor is not structurally relevant to the stage.

Table 1: Stage Archetypes

The uranium fuel cycle is disaggregated into 18 stages spanning upstream, midstream, and downstream segments (see Appendix B for full stage definitions). This analysis focuses on stages 1-8, which constitute the front-end of the fuel cycle and represent the primary supply chain vulnerabilities and coordination opportunities for the Triad. Back-end stages (9-18) involve different policy considerations including waste management, proliferation risks from reprocessing, and long-term repository development.

Key Structural Insights

Across the uranium fuel cycle, the scoring reveals a clear structural pattern. Upstream stages are highly shaped by resource location and show limited complementarity across the Triad, meaning coordination cannot easily relocate production. However, there is still an opportunity for coordination to help improve upstream supply through regulatory alignment for mines located in allied countries. Midstream stages, especially conversion, enrichment, and HALEU production, combine high geopolitical exposure with high complementarity potential, making them the most actionable targets for coordinated investment. Downstream stages retain important industrial strengths but remain dependent on secure midstream fuel supply.

The central finding is that midstream processing is the primary leverage point for trilateral coordination. It is the only segment where vulnerability, feasibility, and allied complementarity consistently intersect.

Stage-by-Stage Structural Analysis

This section applies the CFAF results to each segment of the uranium fuel cycle, translating factor scores into strategic guidance. Each segment is presented in three parts. The structural profile summarizes what the factor-based scoring reveals about the segment's structural characteristics. The analysis interprets those results in the context of current market and geopolitical conditions—what the scores mean for supply security in practice. The coordination strategy identifies the specific type of action the structural profile supports and bridges the detailed recommendations in the following section. Taken together, the four segments reveal a clear investment hierarchy: the urgency and feasibility of trilateral coordination increase sharply as you move from upstream mining (geology-bound) to midstream processing (industrially flexible) and decline downstream where existing Triad capabilities are strong.

CFAF Stages	Geopolitical Risk	Coordination Priority
Upstream (Stages 1-4) Exploration → Milling	Moderate	Secure access via offtake & equity - do not attempt relocation
Midstream (Stages 5-6) Conversion & UF ₆ Handling	High	Expand allied capacity; underwrite with trilateral offtake contracts
Midstream (Stages 7-14) Enrichment (LEU & HALEU)	Critical	Highest-priority capital intervention; HALEU requires near-term emergency action
Downstream (Stages 15-18) Fabrication & Operations	Low-Moderate	Maintain existing strength; vertical integration; advanced fuel R&D

Table 2: Summary of the risk and priority finding for the CFAF stages

Upstream Segment: Exploration, Delineation, Permitting, and Extraction (Stages 1-4)

Structural Profile: Upstream stages are defined by one overriding structural constraint: geography. Factor scores show consistently high Resource Dependence (Factor 1) and consistently low Trilateral Complementarity (Factor 8) across all four stages. This combination—anchored to where deposits exist, not where industrial capacity is concentrated—means coordinated industrial policy cannot relocate upstream activities. What varies across stages is operational intensity: early exploration and delineation require relatively little infrastructure, while extraction and milling become progressively more sensitive to local operating conditions and regulatory environments.

Analysis: The geological distribution of uranium sets hard limits on what trilateral coordination can achieve upstream. While Australia has the most uranium of any country in the world at roughly one-third of global reserves, it remains the world’s third ranking producer. Kazakhstan accounts for roughly 40% of global mine output, driven by low-cost in-situ recovery from favorable geology. Canada's Athabasca Basin hosts some of the world's highest-grade deposits—ore grades of 10-20% U₃O₈, compared to a global average

below 0.3%. These structural advantages cannot be replicated through policy or investment in other jurisdictions (World Nuclear Association, 2026b).

The U.S. holds a meaningful but constrained upstream position. Identified reserves of approximately 300,000 tU at under UAD 130/kg represent roughly 4% of global identified resources—comparable in scale to Namibia—and equivalent to approximately 14 years of current U.S. reactor requirements at ~21,000 tU/yr. However, this is primarily a policy and economic constraint rather than a geological one. In 2023, domestic production supplied less than 1% of U.S. reactor needs, not because the resources are absent but because permitting timelines extend 7-10 years under current regulatory frameworks and because U.S. mining costs exceed world market prices set by lower-cost Kazakh in-situ recovery operations. The Nuclear Innovation Alliance has identified a substantial inventory of undeveloped U.S. sites that could support increased output if price and policy conditions shifted. Japan has virtually no viable domestic deposits. South Korea produces a negligible share of global output. Self-sufficiency in mining is therefore geologically impossible for the Triad.

Geopolitical exposure in the upstream segment increases from low (exploration) to moderate-to-high (extraction and milling), reflecting concentration of active production rather than scarcity of resources globally. Uranium deposits are geographically distributed enough to avoid single-point failure at a system level—but the Triad's actual access to those deposits is mediated through contracting and equity relationships that are currently under-coordinated.

Key Insight: *The CFAF scoring reveals a precise strategic boundary: upstream coordination is about securing access to deposits that already exist, not building new ones. Joint equity stakes and long-term offtake agreements are the only effective instruments; domestic mining programs take a decade and are unlikely to be cost-competitive.*

Coordination Strategy: Because upstream stages cannot be relocated, the coordination strategy must focus on securing access through commercial and diplomatic mechanisms. The Triad should prioritize joint equity participation in production assets within allied partner countries (Canada, Australia, and Namibia), combined with coordinated long-term offtake agreements that reduce intra-allied competition for the same supply. Japan's existing trading company investments (Itochu Marubeni-TEPCO in Kazakhstan) demonstrate that this model is commercially viable and can be formalized and extended. Strategic uranium stockpiling during market surplus periods provides additional disruption buffer without requiring domestic mining self-sufficiency.

Midstream Segment: Conversion and UF₆ Handling (Stages 5-6)

Structural Profile: Conversion and UF₆ handling mark the point at which the structural character of the fuel cycle changes fundamentally. Unlike upstream stages, these activities show low Resource Dependence (Factor 1)—they can be located anywhere with appropriate industrial infrastructure—and high scores across all other factors: technological proximity (Factor 2), institutional thickness (Factor 3), business environment sensitivity (Factor 4), policy commitment (Factor 5), geopolitical risk (Factor 7), and trilateral complementarity (Factor 8). This uniform high-profile across catalytic and security factors identifies conversion as a structurally actionable stage: simultaneously exposed and amenable to intervention.

Analysis: Conversion and UF₆ handling represent the first stage at which structural constraints relax and coordinated intervention becomes feasible. These stages exhibit uniformly high scores across all foundational and catalytic factors indicating deep reliance on industrial capabilities, infrastructure, and policy support, but no dependence on fixed resource geography.

At the same time, high geopolitical exposure (Factor 7) reflects the concentration of global conversion capacity, while high complementarity (Factor 8) indicates that production can be distributed across partner economies. The absence of variation across these factors suggests that vulnerability is systemic rather than stage-specific.

This combination, high exposure and high complementarity, marks conversion as a structurally actionable stage. Unlike upstream activities, these processes can be relocated and scaled within the Triad, making them a viable target for coordinated capacity expansion.

Conversion exhibits the structural characteristics most amenable to Triad coordination. The process transforms U₃O₈ (yellowcake) to UF₆ (uranium hexafluoride) through wet or dry chemical processes. The wet process (used by ConverDyn, Cameco) dissolves yellowcake in nitric acid, extracts uranium using tributyl phosphate (TBP) solvent, and converts to UF₆ using hydrogen fluoride and fluorine gas. The dry process (used by Orano) involves direct fluorination.

All three Triad nations possess adjacent industrial capabilities: chemical processing (petrochemicals, pharmaceuticals), fluorine chemistry (aluminum smelting, refrigerants, semiconductors), materials handling for hazardous substances (HF, fluorine gas), and precision process control. The U.S. has extensive chemical industry infrastructure. Japan operates world-class fine chemicals and specialty materials sectors. South Korea's petrochemical industry (SK Innovation, LG Chem, Lotte Chemical) provides relevant expertise.

Key Insight: Conversion capacity cannot be taken for granted. The six-year ConverDyn shutdown shows that Western facilities will exit the market when demand signals are absent. Trilateral offtake commitments are the mechanism that keeps strategic capacity online—not new construction alone.

Coordination Opportunity: The coordination priority for conversion is capacity assurance through demand commitment. ConverDyn expansion to 60-70% of U.S. needs is commercially viable if backed by ten-to-fifteen-year Japanese and South Korean offtake contracts that improve financing certainty. Longer-term, the development of South Korean conversion capacity, potentially through KEPCO Nuclear Fuel or Korea Atomic Energy Research Institute partnerships supported by U.S. technology sharing, would add a third Triad node, eliminating single-country concentration in the Western conversion base. Coordinated UF₆ stockpiling among Triad nations provides a near-term disruption buffer while capacity expansions proceed.

Midstream Segment: Enrichment and Advanced Processing (Stages 7-14)

Structural Profile: Enrichment stages exhibit the most consistent high-risk structural profile in the entire fuel cycle. Factor scores show low Resource Dependence (Factor 1)—enrichment facilities can be located anywhere with reliable industrial infrastructure—and uniformly high scores across all other factors, including the highest Geopolitical Risk (Factor 7) and Trilateral Complementarity (Factor 8) scores in the analysis. This combination distinguishes enrichment from all other stages: it is simultaneously the most vulnerable point in the chain and the most amenable to coordinated intervention.

Analysis: Russia's Rosatom controls approximately 43% of global enrichment capacity—the largest share held by any single entity in any stage of the fuel cycle. The U.S. enacted the Prohibiting Russian Uranium Imports Act in May 2024, phasing out Russian enriched uranium through 2040. This legislative decoupling creates a structural supply gap that has not yet been filled by new Western capacity decisions. China's CNNC is expanding rapidly to fill that gap—currently at approximately 16% of global enrichment capacity—which would substitute one adversarial dependency for another rather than resolving the underlying structural problem.

Enrichment is the single most critical chokepoint in the Triad's fuel cycle for three compounding reasons that must be understood together. First, the U.S. has only one significant domestic enrichment facility: Urenco USA in Eunice, New Mexico (~4.9 million SWU/yr). This output is insufficient for domestic U.S. reactor requirements of about 15 million SWU/yr annually, leaving the country structurally dependent on enrichment imports. Second—and this is what makes the chokepoint trilateral rather than merely bilateral—

Japan and South Korea face legal constraints on developing independent enrichment capabilities. Japan's bilateral agreements limit enrichment activities; South Korea's 123 Agreement with the U.S. explicitly restricts its enrichment rights. Neither nation can independently close the gap created by reduced Russian supply. The result is that the entire Triad's enrichment security effectively rests on a single U.S. commercial facility plus imported services, with Russia and China collectively controlling roughly 59% of global capacity. Third, enrichment technology is subject to extraordinary proliferation controls as dual-use technology capable of producing both reactor fuel and weapons-grade material. This means capacity cannot simply be licensed or transferred across borders; it must be built within tightly governed institutional frameworks, a process requiring years of regulatory lead time.

HALEU enriched to 5-20%, required for most advanced reactor and SMR designs, represents an acute crisis within an already critical stage. Russia is currently the only HALEU producer at commercial scale. The U.S. has begun rebuilding domestic capability through Centrus Energy's Piketon, Ohio facility, which delivered 20 kg in November 2023 and is operating at approximately 900 kg/yr, a demonstration-scale output that is more than two orders of magnitude below the Department of Energy's projected U.S. demand of 50 metric tons per year by 2035. Without a step-change in investment, this gap will delay advanced reactor deployment across all three Triad economies. China is developing HALEU capability, but production scale remains unclear and the geopolitical risk profile is equivalent to Russia's.

Key Insight: *For conventional LEU enrichment, Western alternatives exist but need expansion—Urenco and Orano can grow if demand is guaranteed. For HALEU, there are no Western commercial alternatives at scale. This is not a market gap that will self-correct; it requires government-backed investment with committed offtake, modelled on COVID-19 vaccine procurement. The window for proactive investment is closing as enrichment facilities take 5–7 years to reach full operation.*

Coordination Opportunity: Enrichment is the highest-priority intervention point for trilateral coordination, and the stage where government action is most directly required. The strategy has two parallel tracks. For LEU enrichment, the near-term mechanism is demand aggregation: a trilateral commitment to purchase 15–20 million SWU/yr collectively from allied suppliers (Orano, Urenco, JNFL, Centrus) at contracted price floors removes the demand uncertainty that has historically blocked private enrichment investment. For HALEU, the mechanism is public procurement: take-or-pay contracts similar to the U.S. HALEU Demonstration Program, extended to commercial scale, with Japanese and Korean governments committing HALEU demand for their advanced reactor programs to provide market certainty for producers. Allied co-investment, particularly South Korean equity

participation in Centrus Piketon, enabled by a 123 Agreement supplement, would provide both capital and political validation.

Downstream Segment: Fabrication, Reactor Operations, and Back-End Management (Stages 15-18)

Structural Profile: Downstream stages differ structurally from everything upstream. Resource Dependence (Factor 1) is low—fabrication and reactor operations are located by electricity demand and reactor siting, not geology, and there is no requirement for the large-scale infrastructure investment that defines midstream stages. What varies significantly within the downstream segment is Market Structure (Factor 6): fuel fabrication is tightly integrated with reactor-specific design requirements and customer relationships, while reactor operations and back-end management are regulated, location-specific activities with low competitive dynamics. Geopolitical exposure is moderate in fabrication and declines through operations to low in waste storage and disposal, which are governed domestically.

Analysis: Fuel fabrication is an existing area of Triad industrial strength. Westinghouse (Cameco-Brookfield, facilities in the U.S., Sweden, U.K., and Spain), Global Nuclear Fuel (GE Vernova-Hitachi), Mitsubishi Nuclear Fuel, and KEPCO Nuclear Fuel collectively serve the majority of Triad reactor requirements with established technical capability. The Triad maintains technological leadership through decades of accumulated operational experience, quality control systems, and close integration with reactor vendors. The market is meaningfully more competitive than upstream stages: the top four allied fabricators hold approximately 43% of global capacity, compared to Russian share of approximately 22%, a more balanced structure that reduces single-point dependency risk (Rosatom's TVEL remains a significant global supplier, particularly for VVER-design reactors).

The critical caveat is that downstream strength is structurally hostage to midstream vulnerability. Fuel fabricators require a secure, consistent supply of enriched uranium dioxide as their primary input. Without resolved conversion and enrichment capacity, fabrication facilities cannot operate regardless of their technical capabilities or market position. The Westinghouse acquisition by Cameco-Brookfield (\$8.2 billion, November 2023) which integrates Canadian uranium mining directly through to fuel fabrication, is the clearest current example of how vertical integration can reduce this exposure and represents a model for broader Triad supply chain architecture.

Back-end management, including interim spent fuel storage and long-term geological disposal, involves distinct policy considerations (waste governance, reprocessing proliferation risks, and repository development timelines) that fall outside the trilateral

investment coordination framework addressed in this report. These stages are domestically governed and do not present the same cross-border coordination opportunities or urgency as midstream processing.

Key Insight: *Downstream capability is a Triad asset worth protecting, not a vulnerability requiring emergency action. The strategic priority is ensuring midstream supply security that allows fabrication facilities to operate, not new investment in fabrication itself, which is already competitive and well-distributed across the Triad.*

Coordination Strategy: The downstream coordination priority is maintenance and vertical integration, not new capacity. Enhanced coordination should focus on three areas: standardizing fuel assembly designs across allied reactor fleets to increase production flexibility and reduce dependency on reactor-specific supply chains; joint fuel qualification testing and technology sharing for advanced fuel types (accident-tolerant fuels, mixed-oxide fuel for SMR applications) to accelerate deployment of innovative designs; and coordinated stockpiling of enriched UO_2 and finished assemblies as a near-term buffer against midstream disruption. The GNF joint venture (GE Vernova-Hitachi) already embodies trilateral cooperation in downstream fabrication and can serve as an institutional template for deeper coordination.

Priority Areas for Trilateral Coordination

Not all segments of the fuel cycle are equally amenable to intervention; priority must be given to midstream processing, where structural vulnerability aligns with feasibility of coordinated investment. A central constraint on scaling nuclear fuel-cycle capacity is a self-reinforcing investment gap: suppliers are unwilling to invest in new capacity without credible long-term demand signals, while project owners, utilities and governments hesitate to commit without assured supply. This dynamic suppresses capacity expansion across conversion, enrichment, and HALEU production, reinforcing existing structural vulnerabilities (Nuclear Scaling Initiative, 2026). The following priority areas identify where coordinated trilateral investment can most effectively reduce structural fuel-cycle vulnerabilities over the next decade.

Priority 1: Immediate Expansion of Allied Conversion and Enrichment Capacity

The near-term objective is rapid expansion of allied midstream capacity to reduce structural dependence on external suppliers. Existing facilities provide a foundation for scaling, but current expansion plans remain insufficient without coordinated demand signals and capital alignment. Fuel-cycle constraints are sequential and interdependent; bottlenecks in

enrichment, deconversion, or fabrication cannot be addressed in isolation and must be scaled in parallel to avoid shifting constraints downstream (Nuclear Scaling Initiative, 2026).

Coordinated investment approach: While anchored by the Triad, effective implementation requires coordination across a broader network of allied partner economies that already hold critical midstream capabilities. The U.S. would prioritize HALEU and advanced enrichment technologies through Centrus, potentially supported by Korean co-investment. The U.S. could also pursue large-scale LEU enrichment expansion, backed by Japanese and South Korean offtake commitments that improve financing certainty. Japan would focus on incremental expansion of domestic enrichment capacity at the Rokkasho facility supported by allied demand guarantees and regulatory streamlining. Canada, led by Cameco, would concentrate on conversion capacity expansion and upstream mining supply. Collectively, this approach would create a distributed allied enrichment architecture capable of absorbing a larger share of global demand while reducing single-point dependency risks. This approach would establish a distributed, allied-controlled enrichment architecture capable of materially displacing Russian supply.

Priority 2: Collective HALEU Production Capacity Development

While midstream LEU capacity can be expanded incrementally, HALEU availability is the binding constraint on next-generation advanced reactor deployment across the Triad. Current demonstration-scale production must transition rapidly to commercial-scale output supported by coordinated public and private investment.

Actions needed: The Triad should pursue jointly financed HALEU production facilities co-located with existing enrichment infrastructure to minimize capital costs and licensing timelines. Governments should align procurement mechanisms, building on the U.S. HALEU allocation program and parallel advanced reactor deployment plans in Japan and South Korea, to provide long-term demand visibility for producers. Technology collaboration among fuel cycle operators across the U.S., Japan, and South Korea should be formalized to accelerate scale-up and share operational learning curves. In parallel, partners should expand joint R&D into next-generation enrichment technologies, including advanced laser-based enrichment approaches currently under demonstration (World Nuclear News, 2025). If coordinated demand signals are absent, private capital is unlikely to fund large-scale enrichment and conversion expansion at the necessary speed, regardless of underlying market need. Without coordinated scale-up, HALEU supply will delay or constrain advanced reactor deployment across all three economies.

Priority 3: Strategic Upstream Coordination

Although midstream capacity remains the most immediate constraint, diversified and secure upstream supply will be essential to sustaining long-term trilateral fuel-cycle resilience. Japan's prior overseas uranium investments like Itochu-Kazatomprom (3,000 tU over 10 years) (World Nuclear Association, 2026b), and Marubeni-TEPCO in Kazakhstan (40% of Kharasan Mine Project) demonstrate the feasibility of coordinated equity strategies and provide a useful template for broader allied engagement (World Nuclear Association, 2021).

Coordinated investment approach: The Triad should pursue selective joint equity participation in resource-rich partner countries to diversify supply while avoiding costly pursuit of full domestic mining self-sufficiency. Priority actions include expanded joint positions in Canadian production assets, coordinated engagement with Kazakh producers where politically and commercially viable, and targeted partnerships with Australian and Namibian developers to broaden geographic diversity of supply.

In parallel, the Triad should establish a standing trilateral procurement coordination mechanism to align long-term offtake commitments, reduce intra-allied competition for supply, and improve financing conditions for new mining developments. Collectively, these measures would strengthen upstream resilience while reinforcing the broader midstream expansion strategy. Taken together, these priorities define a coordinated strategy centered on midstream expansion, supported by upstream access and downstream integration.

Conclusion

The uranium fuel cycle presents a clear case for coordinated trilateral action. Unlike other critical minerals, uranium's dual-use nature creates unique proliferation constraints that complicate its management and security. The combination of Russian dominance alongside the rapid expansion of Chinese capabilities, creates structural exposure that cannot be addressed through unilateral action.

The window for proactive coordination is narrowing. With the recent sanctions on Russian capacity, including the U.S. ban on Russian low-enriched uranium enacted in May 2024, the geopolitical landscape is shifting. Concurrently, Chinese capacity is expanding to fill the gaps left by Russian supply, intensifying the urgency for allied nations to act. Demand for uranium is projected to grow by 28% by 2030 and potentially double by 2040, driven by increasing reliance on nuclear energy for decarbonization. The five-to-ten-year lead times for capacity expansion create conditions for supply crises if coordination efforts are delayed.

The Triad possesses the necessary technical capabilities, financial resources, institutional depth, and political alignment to build resilient uranium supply chains. This analytical framework provides a structured pathway for translating strategic intent into actionable investment priorities. It enables policymakers to move from generalized calls for resilience to specific, defensible projects that can enhance allied security before vulnerabilities crystallize into crises. The next five years represent a narrow window to reshape the fuel cycle before demand growth and geopolitical realignment lock in existing dependencies.

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Appendices

Appendix A: CFAF Structural Factor Definitions

Each uranium supply chain stage is evaluated across eight structural factors. These factors assess how stages are shaped by resource constraints, industrial systems, coordination requirements, and structural risks—-independent of specific geographies or current market conditions.

Foundational Conditions

Factor 1: Resource & Input Advantage

Extent to which the stage is structurally anchored to non-relocatable resources, input characteristics, or natural conditions.

Factor 2: Related Variety & Technological Proximity

Extent to which the stage is structurally enabled by shared technologies, inputs, skills, or knowledge from adjacent industries.

Factor 3: Institutional Thickness

Extent to which the stage depends on formal systems for standards, certification, skill formation, and knowledge development.

Catalytic Conditions

Factor 4: Business Environment Dependencies

Extent to which the stage depends on energy, infrastructure, operational stability, and controlled operating conditions.

Factor 5: Policy & Coordination Dependency

Extent to which the stage requires non-market coordination, regulatory frameworks, long-term alignment, or collective action to operate or scale.

Factor 6: Market Interaction & Feedback Dependency

Extent to which the stage depends on multi-actor interaction, customer–producer coupling, and iterative development or feedback loops.

Security & Resilience Conditions

Factor 7: Geopolitical & Supply-Chain Risk Exposure

Extent to which the stage is structurally prone to concentration, bottlenecks, or chokepoint dynamics.

Factor 8: Structural Decomposability & Complementarity Potential

Extent to which the stage can be separated, distributed, and recombined across actors or systems, enabling complementary specialization.

Appendix B: Uranium Supply Chain Stage Definitions

The uranium fuel cycle is disaggregated into 18 generic stage archetypes spanning exploration through spent fuel management across upstream, midstream, and downstream segments:

- 1 Geological Survey & Exploration** - Identifying uranium deposits through geological mapping, geophysical surveys, and exploratory drilling
- 2a Resource Delineation** - Defining the size, grade, and spatial characteristics of uranium resources through detailed drilling and analysis
- 2b Permitting & Regulatory Approval** - Securing environmental, safety, and operational approvals required to initiate uranium extraction activities
- 3 Extraction / Mining** - Extracting uranium ore through underground, open-pit, or in-situ recovery methods
- 4 Milling & Concentration (U_3O_8 / Yellowcake)** - Processing mined ore to produce uranium oxide concentrate
- 5 Conversion (U_3O_8 to UF_6)** - Transforming uranium oxide into uranium hexafluoride (UF_6) as a precursor for enrichment
- 6 UF_6 Handling, Storage & Logistics** - Managing the storage, transportation, and handling of UF_6 under controlled conditions
- 7 Enrichment (LEU 3–5%)** - Increasing the concentration of U-235 from natural levels (~0.7%) to 3–5% for conventional reactor fuel
- 8 Enrichment (HALEU 5–20%)** - Increasing the concentration of U-235 to 5–20% for advanced reactor applications
- 9 Deconversion (UF_6 to UO_2 or Other Forms)** - Converting enriched UF_6 into uranium dioxide or other usable fuel forms
- 10 Fuel Material Production (Powder & Pellets)** - Producing fuel-grade uranium powder and fabricating it into ceramic pellets

- 11 Fuel Qualification, Testing & Licensing Support** - Conducting testing, validation, and regulatory certification of fuel designs and materials
- 12 Nuclear Material Transport & Security** - Transporting nuclear materials across the supply chain under strict safety and security protocols
- 13 Cladding & Structural Components Production** - Manufacturing metal cladding and structural components used in fuel assemblies
- 14 Component Verification & Quality Assurance** - Ensuring compliance with technical specifications through inspection, testing, and quality control processes
- 15 Fuel Fabrication (Assemblies)** - Assembling fuel pellets, rods, and components into finished reactor-ready fuel assemblies
- 16 Reactor Operations** - Utilizing nuclear fuel within reactors to generate electricity
- 17 Spent Fuel Storage (Interim)** - Cooling, safeguarding, and temporarily storing newly discharged spent fuel from operating commercial reactors before reprocessing, conditioning, or final disposal.
- 18 Waste Conditioning & Geological Disposal** - Preparing radioactive waste for long-term isolation and disposal in geological repositories

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