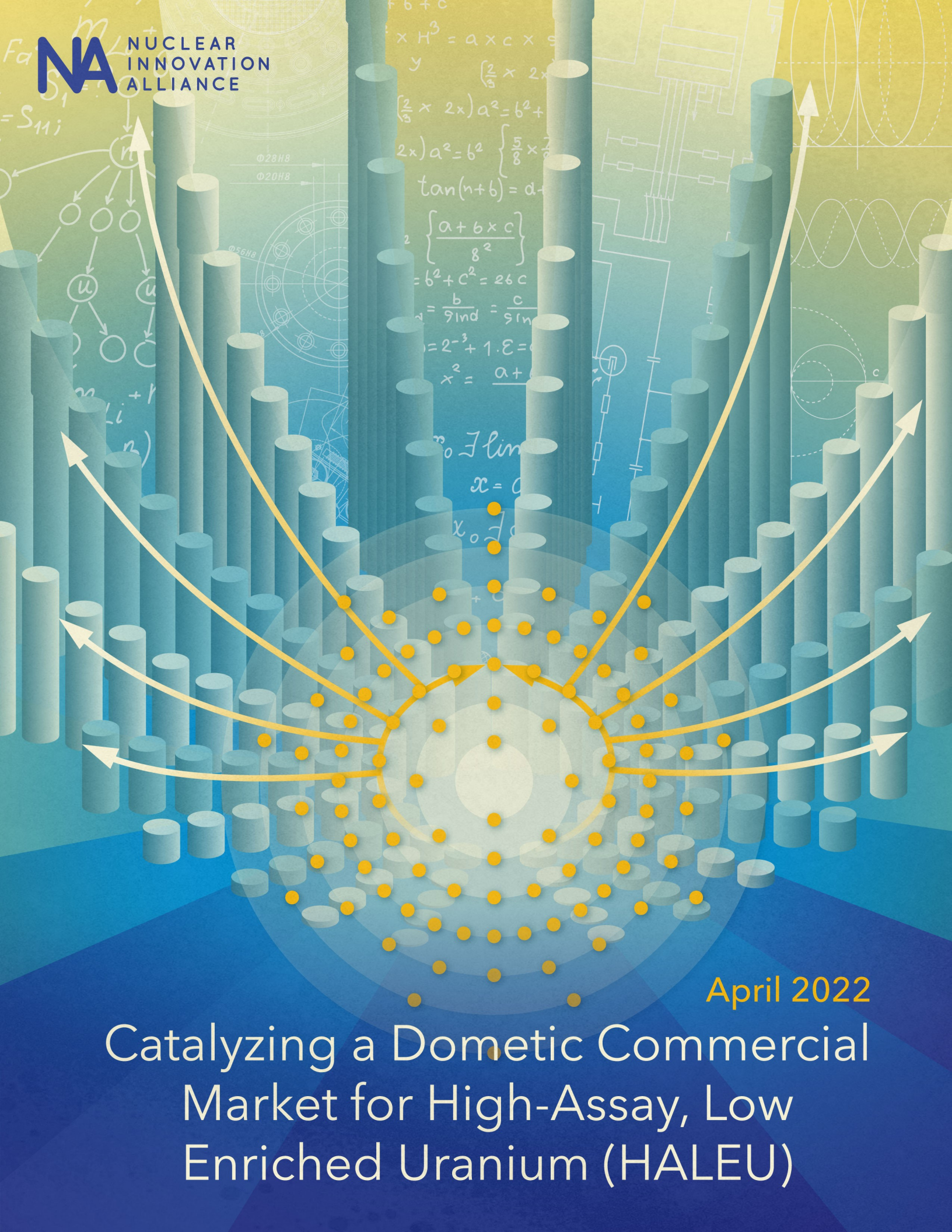


April 2022

# Catalyzing a Dometic Commercial Market for High-Assay, Low Enriched Uranium (HALEU)

# *Catalyzing a Domestic Commercial Market for High-Assay, Low-Enriched Uranium (HALEU)*

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Disclaimer:
The views expressed herein are those of the author(s) and the Nuclear Innovation Alliance.

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## Executive Summary

Successful commercialization of advanced reactors will increase the likelihood and lower the costs of achieving the world's climate goals. A commercially viable High Assay, Low-Enriched Uranium (HALEU) fuel cycle is critical to the successful deployment of many advanced reactor technologies.

Global supply of HALEU is currently dominated by a single company: the Russian state-owned enterprise TENEX. Reliance of future advanced reactor HALEU fuel cycles on a single, state-owned company creates significant economic and political risks. The February 2022 Russian invasion of Ukraine and the resulting geopolitical and commercial uncertainty is a stark warning against the overreliance on TENEX as a short-term or long-term fuel cycle partner for advanced reactor development projects. A diverse, reliable, and commercially viable HALEU fuel cycle is essential for the successful deployment of advanced reactors.

The main challenge of developing a mature commercial HALEU fuel cycle is that high assurance of long-term HALEU demand is needed to justify significant capital investments by fuel cycle companies, while high assurance of near- and mid-term HALEU availability is needed to support the business case for the deployment of advanced reactors. Federal policy and investment to jumpstart HALEU fuel cycle activities could help provide these initial market signals and catalyze development of a mature and sustainable commercial market. This federal investment would be small compared to the enormous climate benefits of successful advanced reactor commercialization.

A future HALEU fuel cycle will incorporate a variety of commercial operations including enrichment facilities, transportation infrastructure, and conversion and deconversion facilities. The absence of market signals to develop new HALEU supply (assurance of long-term commercial demand) and signals that enable long term HALEU demand (assurance of long-term commercial supply) has stalled HALEU fuel cycle infrastructure build-out despite significant government and private investments in advanced reactor technology.

Despite agreement among stakeholders that a commercial HALEU market and HALEU fuel cycle is needed to support advanced reactor commercialization in the United States, there has been limited discussion on the specific market characteristics or program design needed to provide adequate assurance of fuel availability. This paper presents the timing and supply and demand signal challenges associated with the development of a commercial HALEU market and fuel cycle, and outlines potential policy options to help catalyze a commercial HALEU market and HALEU fuel cycle in the United States.

A commercial HALEU market will need to evolve in tandem with the deployment of advanced reactors during the next two decades. The policy mechanisms best suited to support this evolving market will also need to change over time. Recommending different policies during three major time periods over the next fifteen years enables use of specific policy mechanisms to support changing market demands. The major policy insights and recommendations from this paper are:

- Near-term (2022 – 2027) expected demand for HALEU for advanced reactor projects cannot be fully met with new HALEU enrichment infrastructure in the United States due to the time required to design, license, and construct new enrichment facilities and HALEU fuel cycle infrastructure. Alternative federal policies to ensure access to HALEU from domestic or international sources are needed to support near-term advanced reactor commercialization activities.

- Mid-term (2027 – 2034) demand for HALEU for advanced reactors projects could be met with new HALEU enrichment and fuel supply infrastructure in the United States. Market development programs should leverage federal cost-sharing and HALEU purchase agreements to provide demand assurance needed for initial capital investments. These can also leverage long-term federal funding and future government demand for HALEU to reduce federal taxpayer liabilities.
- Long-term (2034 and beyond) supply for HALEU for advanced reactor projects will largely occur after the phase-out of market development programs. Market maturation in the mid term should create sufficient supply and demand signals to develop a sufficient commercial market. Excessive federal government intervention in long-term HALEU markets risks market distortion and creation of artificial supply or demand signals that inhibit market maturation.
- Support for the complete front-end HALEU fuel cycle including enrichment facilities, transportation infrastructure, and conversion/deconversion facilities should be included in market development programs. Program-level identification of possible supply chain bottlenecks that will not be resolved by market supply and demand signals should be used to formulate federal market development programs and help catalyze a robust commercial HALEU fuel cycle.

A commercial HALEU fuel cycle development program can be designed to facilitate a domestic commercial market that supports deployment of advanced reactors. A commercial HALEU fuel cycle development program should be designed around the following activities:

- Evaluation of near-term and mid-term need for domestic HALEU fuel cycle activities depending on the deployment rate of advanced reactors and availability of HALEU from international markets. Both commercial demand and government demand for HALEU to support on-going and new nuclear energy projects should be included in market evaluations.
- Facilitation of near-term procurement of HALEU by providing programmatic support for HALEU procurement by end users.
- Support (financial and programmatic) of supplier investments in new HALEU fuel cycle production and fuel-cycle infrastructure through off-take procurement contracts and cost-share agreements to support mid-term market availability of HALEU. Such government support should be designed to develop market oriented and sustainable supply chains with at least two suppliers for both enrichment and deconversion activities.
- Facilitation of sale of HALEU production purchased by the federal government under off-take agreements to provide additional mid-term HALEU supply assurance.

These activities would help meet the overall goals of a commercial HALEU cycle development program for both HALEU suppliers and users. Market development programs can be designed to meet the needs of different HALEU fuel cycle companies while providing the supply and demand assurances needed to support the successful commercialization of advanced reactors as a climate solution.

## Challenges of commercial HALEU fuel cycle development

The timely development and maturation of a commercial HALEU fuel cycle is critical to successful commercialization of advanced nuclear reactors in the United States. While this market could be domestic or international, there are strategic and economic implications of overreliance on international suppliers with respect to:

- Assurance of HALEU fuel supply for U.S. advanced reactors
- Export of economic benefits of HALEU fuel cycle facilities
- Viability of U.S. advanced reactor exports without assured fuel availability

International commercial supply of HALEU is currently limited to the Russian state-owned company TENEX. While TENEX offers commercial services to U.S. advanced reactor developers, it is not clear if TENEX has the capacity to satisfy all emerging HALEU demands or if sole-source international contracts would provide sufficient HALEU fuel assurance for U.S. advanced reactor developers.

The February 2022 Russian invasion of Ukraine demonstrated the economic and political risk of overreliance on Russia for the commercial supply of HALEU. Sanctions, tariffs, import and export constraints, and voluntary or state-mandated prohibitions on purchase of material or services from Russian companies result in short-term disruptions and long-term uncertainty on availability of HALEU from TENEX. While Russian supply of uranium for commercial reactors was historically resilient to geopolitical tensions, the brazen Russian invasion of Ukraine is a serious concern for advanced reactor developers seeking reliable fuel cycle partners for advanced reactor development projects.

Catalyzing a mature commercial market and a robust supply chain for the HALEU fuel cycle is important to providing sufficient fuel availability assurance for continued advanced reactor investment. Additionally, while internationally sourced HALEU would be acceptable for civilian commercial reactors, it may not be acceptable for certain US government programs including defense or national security related programs directed by the Department of Defense and Department of Energy.

Despite stakeholder agreement that a domestic commercial HALEU market and fuel cycle is needed, there has been limited discussion of the market characteristics needed to provide adequate assurance of fuel availability. Furthermore, commercial investment in HALEU supply infrastructure requires adequate assurance of future HALEU demand from advanced reactor developers and other end users. Without high-confidence demand signals, private companies will not be able to secure the capital investments to build the HALEU supply infrastructure needed to provide adequate assurance of fuel availability.

Enabling the timely creation and maturation of a commercial HALEU market requires policies that support the development of HALEU production considering both supply and demand. Industry confidence necessary to catalyze market development is achieved when:

- HALEU users and advanced reactor developers (demand side) have adequate confidence that HALEU is available at stable and cost-competitive levels to meet commercial demand, and that supply can be scaled economically to meet changing commercial demand; and
- HALEU suppliers including enrichment, transportation, and conversion/deconversion infrastructure companies (supply side) have adequate confidence that demand will be sufficient to justify investments at reasonable scale and predictable over a multi-year timeframe.

A new program to catalyze domestic commercial HALEU market development can help ensure both demand- and supply-side confidence by addressing the underlying material availability and demand-assurance challenges.

Creation of a program to help catalyze commercial HALEU market development requires policymakers to address the following questions:

- What are the success criteria for a domestic commercial HALEU market and advanced reactor fuel cycle?
- What supply and demand signals are needed to support market development?
- How can policy interventions support the development of these signals?
- How can a HALEU market development program be designed to catalyze near-term market development without distorting long-term market stability?
- What role do international markets play in development of a domestic commercial HALEU market?

This paper seeks to answer these questions by qualitatively and quantitatively addressing the program goals for a domestic HALEU market development program.

Two important factors are presented as the basis for assessing a HALEU market development program: the desired characteristics of a domestic commercial HALEU market and the timing challenges associated with the development of a commercial HALEU market. These two factors are used as the basis for characterizing a HALEU market development program that provide HALEU to satisfy near-, mid- and long-term market constraints, and ultimately catalyzes the development of a mature domestic commercial HALEU market. Details on implementation options for a commercial HALEU market development program are also presented.

The commercial HALEU market development programs described in this paper are just one formulation and implementation of federal government support to catalyze market development. While the overall program objectives should be clearly defined to provide market predictability to program participants, the final program design must be sufficiently flexible to adjust to changing market conditions and help ensure the final government program meets the commercial needs of HALEU suppliers and users.

## Characteristics of a domestic commercial HALEU market

A domestic commercial HALEU market needs to be responsive to market conditions, have stable or predictable supply and demand signals, and be able to meet changing market demand with cost-competitive supply. The following high-level characteristics are necessary for the development of a domestic commercial HALEU market:

- Assurance of HALEU at cost-competitive prices
    - HALEU must be available at a price low enough to support the cost-competitive production of energy from advanced nuclear reactors. A competitive and resilient domestic market provides the best basis for price discipline and helps provide predictable and stable costs. Note, however, that the cost of fuel may not be a significant component of final energy costs for some advanced reactors.

- Assurance of HALEU availability (near-term, mid-term)
    - HALEU must be available in sufficient quantities to meet commercial development and deployment requirements. Assuring a HALEU supply will involve the production of advanced reactor fuel for initial cores and subsequent reloads, as well as research and development activities. Near- to mid-term availability needs are based on the two long-duration development activities: 4-7 years required for the development and construction of new HALEU enrichment and fuel cycle infrastructure, and 1-2 years required for fabrication and delivery of advanced reactor fuel from HALEU enriched to a specific level

- Assurance of HALEU supply security (mid-term, long-term)
    - In the mid term and beyond, HALEU must be available from reliable commercial suppliers. Advanced reactor customers need assurance that fuel will be available at adequate prices and with reasonable logistics before they make the substantial capital commitments to new plants. Advanced reactor fuel providers also need assured contracts for fuel production with advanced reactor customers before they make the substantial capital commitments for new fuel production facilities. The exact HALEU supply concerns vary between advanced reactors that only fuel once and do not need core reloads, ones that refuel on a recurring basis (e.g., those with an 18-month fuel cycle), and others that refuel continuously. The new fuel demands and timing for advanced reactors may result in different fuel supplier agreements and business plans for advanced reactor fuels as compared with conventional reactor fuels.

- Assurance of HALEU demand security (mid-term, long-term)
    - HALEU demand must be both stable and predictable over mid-term and longer time periods to provide commercial assurances for suppliers to make and maintain infrastructure investments. High capital cost HALEU production facilities (particularly those using centrifuges, the likely technology for initial HALEU production) are best operated with a high capacity factor and constant output. Long-term facility operation is needed to provide a sufficient payback period to amortize capital investment costs. Assurance of demand is needed to justify new investment, continue the operation of existing facilities, spread fixed costs over a longer period of operation, and amortize short-

term HALEU costs. While the near-term (but low volume) HALEU demand assurance may be provided by continued robust federal support for the Advanced Reactor Demonstration Program (ARDP), the magnitude of future HALEU demand associated with subsequent reactor deployments is highly uncertain. The demand associated with the ARDP program alone is too small to support construction of new HALEU production facilities.

This paper proposes example quantitative characteristics to help bound the design of a commercial HALEU market development program. Final quantitative characteristics used to support program design should vary based on feedback from market stakeholders. Consensus on quantitative characteristics may be difficult to achieve based on differing commercial constraints, so policymakers will need to ensure that any quantitative characteristics used to inform policy design will maximize overall likelihood of successful market development.

The following specific quantitative characteristics are presented as example high-level characteristics for a market development program. Selection of benchmark quantitative values enables comparison of different policy options and is based on stakeholder interviews and prior reviews of HALEU fuel infrastructure[1]. These values are not target values or predictions for the prices, quantities, or other quantitative characteristics for a future HALEU market. The values instead are presented to help estimate program cost and demonstrate cost impacts of different policy options. The values used in this paper include:

- Average price for HALEU material at a standard enrichment and standard form
    - Discussions with potential HALEU suppliers suggest that HALEU $UF_6$ prices between $10,000 and $15,000 per kgU could be achievable based on current technology considerations. This paper will assume an average price for HALEU $UF_6$ enriched to 19.75% of $15,000 per kgU to better enable comparison of policy options. The actual material cost will vary depending on the specific suppliers, enrichments, forms, and production. This value is not a target cost, but an upper estimate cost to facilitate comparison of policy options.

- Market availability of HALEU fuel cycle infrastructure that can enable near-term delivery of initial core loads for first of a kind (FOAK) projects
    - For the purpose of discussing policy options, this paper will assume that a quantity of HALEU from markets for near-term usage (2-4 years) should be greater than 20 metric tons of uranium (MTU). This quantity of HALEU could facilitate the initial core load of one to four advanced reactors depending on the specific reactor design.

- Assurance that HALEU fuel cycle infrastructure that can enable mid-term delivery of core reloads
    - The quantity of HALEU available from markets for mid-term usage (4-8 years) should be able to scale to meet refueling needs and long-term planned projects. Utilities and other HALEU end users need HALEU supply assurance for new reactor deployment contract agreements with advanced reactor developers. Utilizing existing infrastructure where cost effective and enabling new supplier infrastructure through a market development

[1] Nuclear Energy Institute, "Establishing a High Assay Low Enriched Uranium Infrastructure for Advanced Reactors".

program should support expansion of HALEU production capacity given sufficient market signals or forward purchases by advanced reactor developers, utilities, and other end users.

- Market assurance of HALEU fuel cycle infrastructure for long-term supply to support continued advanced reactor operations
    - Policies should incentivize the development of multiple commercial suppliers capable of meeting a significant portion of commercial HALEU needs at cost-competitive non-subsidized prices (or suppliers that can scale to meet significant portions of commercial HALEU needs) without on-going federal program support.

- Market assurance of HALEU for mid-term demand to support supplier investment decisions
    - For the purpose of discussing policy options, this paper will assume that high confidence or guarantee of roughly 10 years of purchase of enrichment facility output is likely needed to support supplier investment decisions. Modern uranium enrichment cascade facilities may have design lifetimes of up to 30 years. Assured revenue streams to pay back capital investment are needed to secure financing for new infrastructure development. For example, a 10-year purchase agreement from a 10-MTU cascade investment at the assumed HALEU cost of $15,000 per kgU would require $1.5 billion in committed funding for purchases of HALEU, although some portion of this funding could be recovered by subsequent sale of material.

These quantitative characteristics provide specific goals for a domestic commercial HALEU market development program. Policy interventions can catalyze and accelerate market development, and help ensure that a stable commercial HALEU market is available to support commercialization of advanced reactors in the public interest.

## Timing development of a commercial HALEU market

Adequate supply and demand signals that provide assurance to market participants are a necessary but not sufficient condition for the development of a commercial HALEU market that enables continued investment in deployment of advanced reactors. The supply and demand conditions and constraints on the commercial HALEU market over the next fifteen years can be divided into three phases: near-term, mid-term, and long-term. These three phases characterize how supply and demand challenges and the developing HALEU market will evolve over time. Figure 1 visualizes the three phases and shows expected major demand signals for each phase.

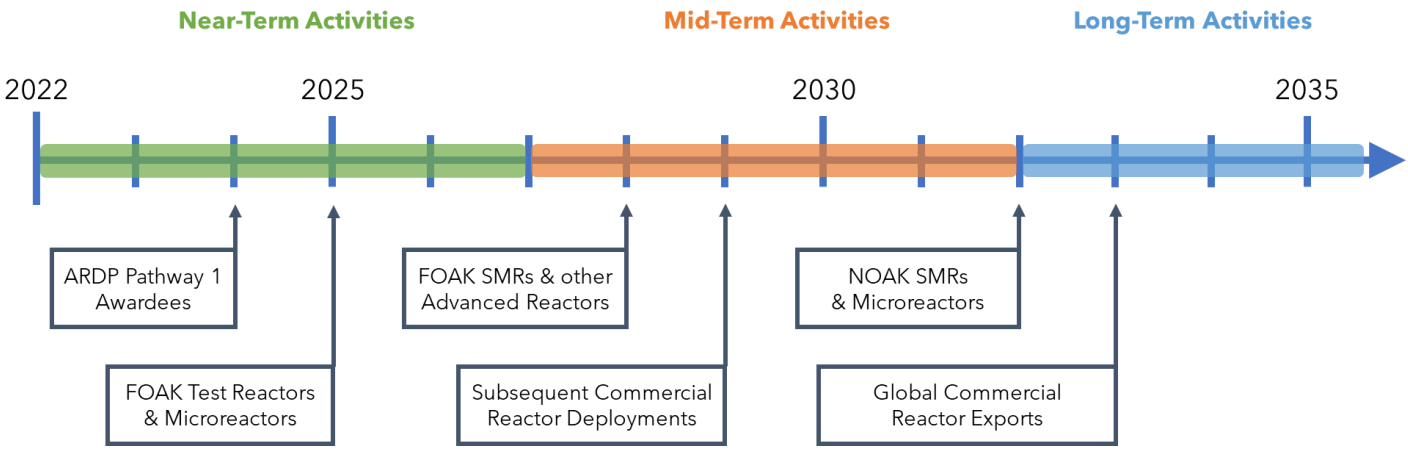


Figure 1. Time phases for a domestic commercial HALEU market development program

Timing of market development is critical to ensuring that fuel is available to meet the deployment objectives of advanced reactor developers. Table 1 describes the demand side and supply side signals that can be expected during each of the three phases.

A market development program that catalyzes a domestic commercial HALEU market will need to evolve over time to meet these changing needs. Designing a market development program with flexible implementation policies will facilitate changes that both enable near-term advanced reactor fueling and build toward long-term success.

Table 1. Timing of Changing HALEU Demand and Supply

| Time Phase | Potential HALEU Demand | Potential HALEU Supply |
|---|---|---|
| Near-term: 2022 through 2027 | • Advanced reactor fuel testing and development activities<br>• Initial HALEU fuel for first-of-a-kind (FOAK) commercial and test reactors including ARDP Pathway 1 awardees and some Risk Reduction awardees<br>• Initial HALEU fuel load for FOAK microreactors, including government programs such as those managed by DOD and NASA | • Operation of Centrus demonstration cascades (capacity of less than 1 MTU/year)<br>• Recovery and downblending of excess material from past DOE fuel programs, including processing of scrap materials from the DOE complex. This material may not be suitable for all reactor developers due to contamination by fission products or other radionuclides<br>• Downblending of highly enriched uranium (HEU) from DOE National Nuclear Security Administration or other existing federal stockpiles<br>• Foreign suppliers (i.e., TENEX) |
| Mid-term: 2027 through 2032 | • Advanced reactor fuel testing and development activities<br>• Initial HALEU fuel for other FOAK commercial and test reactors including Risk Reduction awardees<br>• Core reloads for near-term deployed advanced reactors<br>• Initial HALEU fuel for subsequent deployments of near-term demonstrated advanced reactors<br>• Significant demand variation depending on deployment rates | • New domestic HALEU fuel cycle production facilities that are catalyzed through the HALEU market development program. Supply timing and total supply capacity will vary based on capital investments made in the near term by HALEU suppliers. Note that a 4-5 year project timeline may be needed for new projects.<br>• Foreign suppliers (i.e., TENEX or new market entrants) |
| Long-term: 2032 and beyond | • Advanced reactor fuel testing and development activities<br>• Initial HALEU fuel for other FOAK commercial and test reactors including ARDP Advanced Reactor Concepts (ARC-20) awardees<br>• Core reloads for near-term and mid-term deployed advanced reactors<br>• Initial HALEU fuel for subsequent deployments of mid-term demonstrated advanced reactors<br>• Significant demand variation depending on deployment rates<br>• Additional HALEU demand from DOE, Department of Defense, and NASA nuclear energy projects | • Continued production from mid-term HALEU fuel cycle production facilities<br>• Expanded production from mid-term HALEU fuel cycle production facilities based on demonstrated demand from new or on-going advanced reactor deployments. Note that a several-year project timeline may be needed for capacity expansion at existing facilities but it would likely be less than required for a new HALEU facility.<br>• Foreign suppliers (i.e., TENEX or new market entrants) |

## Outlining a commercial HALEU market development program

The overall goal of a commercial HALEU market development program is to catalyze a competitive market that facilitates commercialization of advanced reactors. A program focused on only near-term activities, while necessary to support demonstration reactors, would place a myopic focus on HALEU supply from existing material stockpiles or foreign HALEU suppliers. Similarly, a focus on long-term activities would not allow industry to meet the fuel demands for first- and second-generation advanced reactors in the near and mid term and would irreparably harm the economic viability of advanced reactor technology to help solve the climate problem. Thus, the primary goal of any commercial HALEU market development program is catalyzing competitive market development in the mid-term time horizon of 2025 to 2032.

Development of the mid-term market requires supporting both the supply side and demand side conditions necessary for a domestic commercial market. Mid-term supplier conditions for success include:

- A cost-competitive price for HALEU to ensure that investment in a HALEU production facility is financially viable. This price will vary based on the supplier business plans and capital payback required to support investments.
- Sufficiently high confidence or guarantee of production purchase (or other revenues) over a multi-year period to support HALEU fuel cycle supplier investment decisions, capital recovery, and returns on investment.

Mid-term demand conditions for success include:

- Cost-competitive price for HALEU to support the business case for advanced reactor operations.
- Sufficiently high market assurance or contractual guarantee of HALEU availability to support the case for FOAK core-reloads (enabling continued operation of near-term advanced reactor projects) and, most importantly, deployment of subsequent advanced reactors (key to the long-term prospects for advanced reactor deployment).

In the mid-term market, demand assurance is most important to satisfy the market conditions needed for suppliers to invest in HALEU production capacity. Mid-term demand for HALEU is subject to significant uncertainty and will vary widely depending on the success of FOAK demonstration programs and/or other government support for advanced reactors. The HALEU demand of the ARDP Pathway 1 awardees alone would not be sufficient in magnitude to support development of one or more commercial HALEU suppliers. As a result, a mid-term commercial HALEU market development program should focus on mechanisms that can provide the mid-term commercial demand assurances needed for supplier capital investment in new HALEU production capabilities. Increased investment in new production capacity will also provide the market assurances of HALEU availability needed by developers to continue advanced reactor commercialization activities and, in particular, by prospective project sponsors to consider commitments to new advanced reactor projects. A holistic market development approach that accounts for both commercial and government HALEU demand can help provide a larger, high-certainty demand signal for HALEU suppliers. This will not only increase the overall volume but theoretically will save taxpayer resources by leveraging commercial facilities and reducing the need for separate government HALEU production infrastructure.

This paper presents three policy mechanisms that can be used to support mid-term HALEU market development:

- Off-take agreement: Program-directed purchase and sale of material from HALEU suppliers. A buy-out option is included as part of the off-take agreement to limit government liability for HALEU purchases if commercial demand for HALEU does not materialize in the mid term.
- Cost-share agreements: Direct program support of infrastructure investments based on a ratio cost-share between the supplier and the federal government. A milestones-based approach is utilized to limit government liability for suppliers that do not meet programmatic targets.
- Cost-share with partial off-take agreement: Direct program support of infrastructure investments with an additional agreement for purchase and directed resale of material. Both milestones and buy-out options should be utilized to limit government liability.

The policy mechanisms most appropriate for a specific supplier may vary depending on its business model and ability to access capital investment funding for new HALEU fuel cycle infrastructure. The goal of the market development program is not to choose which companies or business models succeed within the marketplace, but to catalyze the overall development of the domestic commercial HALEU market through competitive processes.

Selection of policy mechanisms should be focused on maximizing assurance of meeting demands for cost competitive HALEU in the near, mid, and long term. A flexible approach that allows tailoring of the policy mechanism to the supplier based on outcomes helps optimize the use of federal funding to promote market development. Selection of the appropriate policy mechanisms for a commercial HALEU market development program should consider what mechanisms result in the highest likelihood of achieving overall program goals.

This section describes many of the direct financial costs associated with different policy mechanisms. These costs are important to quantify and evaluate, but they need to be contextualized in terms of the benefits associated with a HALEU fuel cycle development program and the costs of failure to provide timely HALEU fuels for advanced reactor projects. The benefits of a successful HALEU fuel cycle development program include the accelerated deployment of advanced reactors as a solution to climate change, the increased export competitiveness of domestic advanced reactor developers, and decreased dependency on international HALEU suppliers. The federal government is slated to invest over $3.2 billion dollars in the ARPD Pathway 1 awardees, both of which require HALEU fuel to operate. Support of the HALEU fuel cycle development program can help facilitate the successful completion of the advanced reactor programs by providing timely and cost-competitive fuel at a fraction of the total ARDP program cost. The economic and societal benefits of a successful HALEU fuel cycle development program far exceed the costs.

## Off-take agreements

Off-take agreements described in this white paper are organized purchases by the program of material from a HALEU enrichment company (and possible subsequent deconversion), and the directed resale of the material into the marketplace. The major benefit of an off-take agreement is that it incentivizes suppliers to make strategic investments to meet both short-term and long-term objectives instead of prescribing specific projects or investments for suppliers. Material purchased by these off-take agreements could be resold by the program to reduce total program costs for taxpayers and more

effectively use the government's unique ability to effectively extend credit (at limited cost) to support long-term private infrastructure investments. The major drawback of an off-take agreement is that the program risks the stranding of purchased material (with significant sunk costs funded by taxpayers) if buyers for the off-take material cannot be found. The U.S. government has potential long-term uses for purchased HALEU (e.g., DOE-leased fuel for research reactors or government-sponsored national security programs). Transfer or sale of HALEU for government use should be included in initial policy development and implementation for a HALEU market development program if U.S. government acquisition of purchased HALEU for DOE or DOD programs is considered a potential outcome for an off-take agreement program.

The first portion of the off-take agreement structure is the forward purchase of material produced by a supplier. The off-take agreements with suppliers are based on:

1. HALEU supplier and user characteristics
    - Timing of HALEU purchases (initial material availability after contracting)
    - Quantity of HALEU purchased per year (including form and enrichment)
    - Duration of HALEU purchases (total duration in years)
    - Price of HALEU purchases (constant purchase price or time varying)
2. HALEU program liability characteristics
    - Quantity of HALEU maintained by the purchase program (total "stockpile" of material available for sale)
    - Guaranteed duration of purchase before optional buy-out (fixed program review window or regular program reviews)
    - Off-take agreement buy-out characteristics (fixed value or calculated buy-out)[2]
3. International HALEU supply
    - Quantity of foreign HALEU available (including form and enrichment)
    - Price of foreign HALEU available (constant purchase price or time varying)
    - Assurance of on-going foreign HALEU availability (market confidence in continued material availability from international suppliers)
    - Existing trade agreements

These characteristics, at a high level, help define an off-take agreement as part of a market development program. The first four characteristics are largely based on the supplier and program constraints that support supplier investment decisions or capital market investment in new production capacity. The second three characteristics are helpful to define program liability associated with excessive purchases of HALEU material that are not ultimately needed by HALEU users and to limit supplier risk associated with capital investments. The off-take buy-out is intended to provide an off-ramp for the federal government's off-take agreement while still protecting the suppliers' return on investment. The final three characteristics relate to the potential impacts of international HALEU suppliers on a domestic market development program. The market effects of international suppliers must be considered when designing and operating a market development program to prevent the creation of an unsustainable and non-viable commercial HALEU market.

[2] Details on the feasibility of a buyout structure are provided below

The second portion of the off-take agreement structure is the resale of purchased material. The resale program is intentionally designed to help facilitate market development by providing short-term stabilizing supply and demand signals. Material purchased as part of an off-take agreement may or may not be immediately sold depending on market conditions or other programmatic factors. As a result, a physical or ledger inventory of material may accumulate that the program may leverage to ensure future supply. The availability of this material for resale is critical to providing high market assurance of HALEU availability to advanced reactor developers and mitigating supply shortages such that the program facilitates both continued supplier operation and deployment of advanced reactors. Principles underlying the material resale should be developed to ensure predictability or stability of sales. Possible principles of material resale include:

- Material sales based on user commitment (and partial advanced payment) to purchase off-take material (coordination of supply and demand signals by program design)
- Material sales at purchase cost plus an overhead cost to maintain a competitive market and protect the government's investment (sale at a predictable price to minimize market distortion)
- The amount of government off-take purchases can be reduced by coordinating direct purchase agreements between AR developers and users, and domestic HALEU suppliers

The exact principles used to develop an off-take agreement should be based on review of conditions that will meet overall market development goals (e.g., economic competitiveness as well as HALEU supply assurance). Under any resale principles, a competitive bid system could be utilized to set final prices and determine sale quantities, helping ensure appropriate market allocation of available material. The revenue generated by these sales could be reinvested into the program to help catalyze future program activities and reduce overall budgetary impacts of the program.

The costs of the HALEU off-take agreements can be characterized in three ways: total purchase cost, held inventory liability, and buy-out liability. The first cost (total purchase cost) represents the total cost of material purchased by the off-take agreement. The total purchase cost is the cumulative purchase total over the course of the agreement. For example, a 5-year off-take agreement for 10 MTU per year at an average cost of $15 million dollars per MTU would have a total purchase cost of $750 million. It is important to note that if the program resells the material back into the market, the proceeds from sales could be reinvested in the HALEU market development program. Reinvestment would enable completion of the offtake agreement with Congressional appropriations less than the total agreement cost.

Off-take agreement payments could be made upon or prior to material delivery depending on the agreement structure. Advanced payment of a significant portion of the offtake agreement to suppliers would decrease the total project financing cost (and the subsequent HALEU material costs) but would decrease the ability of the government to utilize a milestone-based payment structure to help limit project risk. Use of an off-take agreement with an advanced payment mechanism can function, in part, like a cost-share based on the ability to forward fund capital investments.

The second cost (held inventory liability) represents the total liability associated with material that is held in the physical or ledger inventory of material that may be accumulated during program operation based on differences between program purchases and directed resales. The held inventory liability is the integrated cost of the material accumulated by the program net of sales receipts. For example, a total accumulated inventory of 25 MTU at an average cost of $18 million per MTU would have a held inventory

liability of $450 million. Sales could help fully recover the cost depending on the program design, but the inventory is a liability for cash-flow and funding purposes. While the US government could use accumulated HALEU for future federal programs (e.g., DOE-leased fuel for research reactors), government takeover of stranded material for other program uses should not be assumed and would require separate Congressional funding or appropriations. Purchase of HALEU for federal DOE or DOD programs could be an effective way to create a larger, high-certainty demand signal for HALEU suppliers. Transfer or sale programs from unsold accumulated HALEU or incorporation of future federal program needs into off-take agreements should be included in policy development and implementation if federal transfer or sale are an expected potential outcome for an off-take agreement program.

One additional component of the cost of held inventory liability is the cost related to the storage of held material. If the material is physically held by the program, there are costs associated with the construction, modification, maintenance, and operation of infrastructure needed to transport and store material between acquisition and sale. These costs could vary significantly depending on the ability to leverage existing DOE material infrastructure licensed or certified to store HALEU (e.g., Nuclear Materials Management and Storage Program at Y-12) or existing licensed commercial facilities (e.g., existing Category 1 or Category 2 facilities including fuel fabricators) versus the need to develop new material infrastructure to support expected capacity needs. If the material is a ledger inventory held by the suppliers until sale by the program, the responsibility for the cost of physical storage must be settled between the suppliers and the program. Another option is to allow fuel fabricators to use this material as working stock in exchange for free storage, similar to existing commercial practice with low enriched uranium (LEU) for light water reactor fuel manufacturing. Again, these costs could vary significantly based on the existing infrastructure at the facility versus the need to develop new infrastructure to support expected capacity needs. The one-time costs associated with development of infrastructure and on-going costs associated with operation of infrastructure should be included as part of quantification of program costs. These costs, however, will be extremely project- and program-specific, so generic characterization of the costs may not be feasible.

The third cost (buy-out liability) represents the payment that would be provided to suppliers to prematurely end an off-take agreement while still providing sufficient assurance to suppliers that they can recover capital investments. If there is a need to end a HALEU off-take agreement using a buy-out mechanism, it may be possible to mitigate the costs associated with the buy-out while still protecting HALEU supplier investments. The material cost associated with a HALEU off-take agreement can generally be separated into two components:

- the cost of LEU $UF_6$ feedstock already enriched to 4.95% U-235, which is likely to be half or more of the final cost of HALEU, and
- the facility capital-recovery and operating costs associated with enrichment from 4.95% to desired enrichment of U-235.

There is already a mature, international market for LEU $UF_6$ feedstock, so it is possible to resell any unneeded LEU $UF_6$ feedstock associated with the off-take agreements in commercial LEU markets, although there would be price risk associated with market movements between purchase and resale. Reselling or canceling contracts for LEU $UF_6$ feedstock not needed as part of the buy-out agreement would reduce the overall buy-out liability to the portion associated with HALEU-specific costs. A buy-out established as part of the initial procurement agreement could provide supplier assurance on sunk costs

(including capital investments, committed operating costs, dismantling costs, and decommissioning costs), eliminate excess material purchases not needed by to support program activities, and reduce overall program spending.

The buy-out liability varies based on the quantity of material in the off-take agreement, the price of the material in the off-take agreement, the number of years of production bought-out and the proportion of the price representing costs other than feedstock for the supplier. Since only the supplier will know this proportion, a buy-out cost would need to be an element of an agreement solicited by the program and proposed by the supplier as part of an overall offer. The buy-out liability is the product of the cumulative purchase total remaining over the course of the agreement and ratio of the operating cost of a HALEU production facility to the total HALEU cost for the supplier. For example, if capital-recovery and operations costs represent 40 percent% of the unit costs of supply, a buy-out would be significantly smaller than the total remaining purchase cost and would still protect the investments made by the supplier on the promise of continued purchases.

These three costs (total purchase cost, held inventory liability, and buy-out liability) help characterize the costs of the HALEU off-take agreements. Use of the appropriate cost is necessary when comparing the program costs of different supplier market development scenarios.

## Cost-share agreements

Cost-share agreements are programmatic support for HALEU supplier infrastructure investment activities to build HALEU production capacity. The major benefit of a cost-share agreement is that it can provide for the guaranteed construction of infrastructure capacity based on the contractual arrangements. This can reduce the variability of constructed infrastructure capacity based on market forces associated with other programmatic scenarios. Cost-share agreements can enable more effective competition with state-owned international HALEU suppliers. The major drawback of cost-share agreements is that they are an irrecoverable taxpayer subsidy for suppliers and cannot be recovered through traditional cost-recovery mechanisms. Cost-share agreements can also support infrastructure construction that is not otherwise commercially viable (e.g., due to insufficient demand or excessive costs) and result in facilities that cannot operate or expand commercially without additional programmatic support.

The cost-share agreements with suppliers are based on:

1. Scope of cost-share activities (what infrastructure investment can be supported)
2. Quantity of HALEU capacity supported (including form and enrichment)
3. Total cost of infrastructure investment (contract applicable for cost-share)
4. Cost-share ratio (ratio of program support to private support)
5. Cost-share milestone schedule (performance and external funding-based project milestones)
6. Predicted economic competitiveness of final HALEU supplies

These characteristics, at a high-level, help define a cost-share agreement as part of a market development program. These cost-share agreements provide direct support for development of new capital infrastructure. The infrastructure investments could include HALEU production capacity (e.g., enrichment facilities) as well as associated infrastructure needed to support HALEU fuel cycle operation (e.g., deconversion facilities).

The costs of the HALEU cost-share agreements can be characterized in two ways: total contract cost and program liability costs. The total contract cost is a simple description of the total project cost for the infrastructure including both public and private contributions. The program liability cost is the total amount of program funding that is allocated to the supplier subject to successful completion of all milestones based on the total contract cost and the cost-share ratio. This program liability also represents a maximum possible liability associated with project completion. The remaining program liability decrease over the course of the project with the completion of milestones and may be reduced to zero if failure to complete project milestones results in program termination of the cost-share agreement. The program liability cost represents funding that will not be recovered by the program and is a net expenditure by the program to facilitate infrastructure development.

## Cost-share with partial off-take agreement

Cost-share agreements can be combined with a partial off-take agreements to both support initial capital investment and provide partial assurance of long-term demand that is critical to supporting the financing of the private portion of the capital investment. A combined policy support mechanism would require programmatic consideration of the characteristics and factors for both cost-share agreements and off-take agreements.

Cost metrics that combine total liabilities from both the cost-share agreements and partial off-take agreements could be used to help create conditions that provide for equitable program support of different market development policy mechanisms. For example, the terms of both agreements could be varied so that the combination of the buy-out liability costs and program liability costs would be comparable to the buy-out liability costs or program liability costs for other scenarios.

## Designing a commercial HALEU market development program

A commercial HALEU market development program can be designed to facilitate a domestic commercial market that supports commercialization of advanced reactors. The example development program described in this section is designed around four main activities:

- Evaluate near-term and mid-term need for domestic HALEU fuel cycle activities depending on deployment of advanced reactors and availability of HALEU from international markets.
- Facilitate near-term procurement of HALEU by providing programmatic support for HALEU procurement by end users.
- Support (financially and programmatically) supplier investments in new HALEU fuel cycle production and fuel-cycle infrastructure to support mid-term market availability of HALEU.
- Facilitate sale of HALEU production purchased under off-take agreements to provide additional mid-term HALEU supply assurance.

Each of these activities is important to meeting the overall goals of the program for both HALEU suppliers and users. It is important to note that a government program to develop a commercial HALEU market would develop mid-term markets, while leaving long-term market development to the private sector. Long-term demand for HALEU fuel cycle activities will need to provide adequate market signals for continued investment in HALEU fuel cycle infrastructure without continued government intervention.

### Evaluating near-term and mid-term HALEU needs

The first commercial HALEU market development program activity is an evaluation of near-term and long-term need for domestic HALEU fuel cycle activities. The demand for domestic HALEU fuel cycle capacity in the next 5 to 10 years will depend on several factors including:

- Domestic deployment of advanced reactors (number of projects, reactor types)
- Export of domestic advanced reactors relying on U.S. based fuel cycles suppliers
- Availability, costs, and assurance of international HALEU fuel cycle supplies

Each of these factors is subject to significant uncertainty. Low demand for domestic HALEU fuel cycle capacity could result from limited deployment of advanced reactors and robust availability of HALEU fuel from international commercial suppliers (e.g., significant portion of HALEU demand satisfied by existing TENEX infrastructure or other international suppliers). High demand for domestic HALEU fuel cycle capacity could result from widescale deployment of advanced reactors and limited availability of HALEU fuel from international commercial suppliers (e.g., HALEU unavailable from TENEX due to commercial or political constraints). A HALEU development program should be able to catalyze a mature commercial market that can respond to market forces and meet changing demand without continued government intervention.

A market development program must first establish the expected domestic HALEU fuel cycle demand and create adaptable plans that accommodate changing market demand conditions while still providing the supply and demand assurances critical to facilitating market development. Definition of high- and low-confidence demand signals based on the assessed commercial viability of specific projects or developer activities could be used to help better quantify and characterize near- and mid-term HALEU fuel cycle demand. Continued engagement with international HALEU suppliers and policymakers is needed to help

quantify and characterize the commercial and political constraints of international HALEU fuel cycle supply. The 2021 DOE Request for Information related to planning DOE HALEU activities was an important first step in characterizing these activities, but on-going engagement between DOE program managers and stakeholders is needed to assess and evaluate changing market conditions[3].

## Near-term HALEU procurement program

The second commercial HALEU market development program activity is the near-term procurement of HALEU. One of the major challenges of the HALEU market development program is that, in the near term, there is high demand certainty from the initial fuel loads (first cores) for first-of-a-kind SMRs (including ARPD Pathway 1 awardees) and commercial microreactors but limited near-term material supply. New HALEU production infrastructure is expected to take between four and seven years depending on funding, siting, licensing, and construction. As a result, material needed to satisfy the near-term demand must be acquired from existing known supplies or from sources that can be quickly utilized. Unless significant changes occur related to the project lifecycle for new HALEU supply infrastructure, domestic HALEU supply capacity will not be able to meet the near-term needs.

Near-term HALEU supply is, in principle, available from four main sources, each of which carry significant challenges:

- Commercial procurement from foreign suppliers (i.e., TENEX in Russia),
- Production from existing demonstration HALEU enrichment infrastructure (i.e., Centrus American Centrifuge Demonstration program cascades),
- Recovery and downblending of excess material from past DOE fuel programs, including processing of unused or waste materials from across the DOE complex. This material may not be suitable for all advanced reactor developers due to contamination by fission products or other radionuclides, and
- Downblending of highly enriched uranium (HEU) from DOE National Nuclear Security Administration or other existing federal stockpiles

The first source of HALEU for near-term advanced reactor development and deployment could be acquired from foreign suppliers within the framework of existing trade agreements. Natural enrichment uranium and LEU is currently available worldwide as a standardized commodity. Companies in the United States regularly purchase LEU from foreign suppliers including suppliers such as TENEX in Russia. Extension of these commercial programs to the HALEU fuel cycle could be used to provide near-term HALEU for advanced reactor developers while additional HALEU enrichment infrastructure is constructed to provide mid-term supply.

The main challenges associated with this source are the capability of foreign suppliers to scale to meet near-term demand, the transportation infrastructure challenges associated with international HALEU movement, and the economic and political risks of overreliance and funding of foreign HALEU suppliers. The ability of foreign suppliers to meet rapidly increasing near-term demand and successfully navigate international regulatory and supply chain requirements to deliver HALEU has not been demonstrated.

[3] Federal Register: Request for Information (RFI) Regarding Planning for Establishment of a Program To Support the Availability of High-Assay Low-Enriched Uranium (HALEU) for Civilian Domestic Research, Development, Demonstration, and Commercial Use

These foreign HALEU sources could help meet civilian commercial HALEU needs, but they are not acceptable for use in government programs that require U.S.-origin nuclear material including certain defense applications.

The more significant concern over near-term commercial procurement from foreign suppliers is the economic and political risks of overreliance and funding of foreign HALEU suppliers, specifically TENEX. The February 2022 Russian invasion of Ukraine demonstrated the economic and political risk of reliance on Russia for the commercial supply of HALEU. Sanctions, tariffs, import and export constraints, and voluntary or state-mandated prohibitions on purchase of material or services from Russian companies result in short-term disruptions and long-term uncertainty on availability of HALEU from TENEX. Advanced reactor developers have little interest in funding and increasing reliance on international partners and companies that do not have a strong commitment to reliable and sustainable business partnerships.

The second source of HALEU is production for near-term advanced reactor development and deployment from existing demonstration enrichment infrastructure. While technically feasible, this capacity is small compared with projected near-term needs. HALEU production from the Centrus American Centrifuge Demonstration program is limited to less than 1 MTU per year and would not be sufficient to supply the FOAK cores for SMRs or microreactors. Scaled up production of the Centrus demonstration program is not considered feasible in the next 2 years to meet near-term needs and would likely rather be completed as part of a mid-term HALEU supply development program. The Centrus American Centrifuge Demonstration currently only consists of enrichment facilities and there are no public plans for deconversion capabilities.

The third source of near-term HALEU production is material production from the recovery of past DOE fuel programs. Production of HALEU from this material source is likely both limited and expensive. Recovery of HALEU from the Experimental Breeder Reactor II (EBR-II) spent fuel at Idaho National Lab (INL) can produce up to 1 MTU per year but this fuel is limited by DOE policy to usage on the INL site and is not isotopically compatible with some advanced reactors due to the previous use in EBR-II. Recycling of aqueous HALEU and spent fuel from INL and the Savanah River Site (SRS) could produce 1 to 2 MTU per year but would require substantial investment and may also not be compatible with some advanced reactors. Scale-up of these programs would require substantial programmatic and physical investments and are primarily stop-gap measures that would not result in robust new production infrastructure capabilities. It is not clear whether the new processing infrastructure could be brought online faster than construction of new HALEU enrichment infrastructure.

The fourth source of near-term HALEU production is allocation of excess HALEU or downblending of excess HEU from DOE NNSA stockpiles. This material production pathway is challenging programmatically. Production of significant quantities of HALEU via downblending (i.e., 5-10 MTU per year) is technically feasible but requires additional investment in new production infrastructure and capabilities at existing BWXT facilities (the only commercial facility with HEU downblending capabilities). While material downblending is technically well characterized, alignment of programmatic and infrastructure priorities by BWXT would require additional funding and negotiation. This significant investment, however, would only serve as a stop-gap based on existing HEU stockpiles and would not result in robust new HALEU production infrastructure capabilities.

This option would require DOE NNSA to prioritize near-term commercial HALEU availability over long-term mission requirements. The 2021 DOE Request for Information related to planning DOE HALEU activities describes the prioritization challenges for HEU downblending activities[4]:

> Most of NNSA's HEU is reserved for the Naval Reactors program and for use in the nuclear weapons stockpile, and is therefore unavailable for down-blending to use in advanced reactors used for commercial applications. Other HEU in the inventory is allocated to supply research reactors and medical isotope production facilities worldwide, and to meet critical defense and space requirements. After accounting for these requirements on the inventory, the remaining amount of HEU to be down-blended to HALEU for advanced commercial reactors is very limited. If these supplies were redirected to fuel advanced commercial reactors, they would not be sufficient to meet the projected near-term demands for advanced reactor demonstration and deployment. Furthermore, diverting these resources to support advanced reactor demonstration and deployment would compromise vital nuclear security and nonproliferation missions.

While reprioritization of material allocated to other programs is possible, it would require detailed strategic evaluation of material needs in the context of long-term scientific, research, and national security objectives. It is not clear whether both the technical and programmatic requirements could be resolved faster than the construction of new HALEU enrichment infrastructure. Timely Congressional authorization and appropriation, strong Administration leadership, and effective DOE implementation would be critical to meeting near-term HALEU supply needs with downblending of excess HEU from DOE NNSA stockpiles.

Each of these sources has significant challenges but commercial availability of HALEU to domestic developers is critical to the successful completion of the ARDP projects and the broader commercialization and deployment of advanced reactors.

A near-term HALEU procurement program could be used to facilitate important programmatic infrastructure support for procurement from foreign sources. While the DOE would not purchase or directly facilitate purchases of HALEU from foreign sources, the DOE could help develop infrastructure that supports a robust international HALEU market. Specifically, the HALEU procurement program could provide technical and financial support for HALEU transportation infrastructure. Cost-share or other milestone-based contract programs similar to those used for the mid-term HALEU market development programs could be used to rapidly support deployment of transportation infrastructure in a supplier-agnostic manner. This program would enable private companies to pursue near-term commercial arrangements with foreign suppliers while also supporting HALEU transportation infrastructure critical for mid-term and long-term domestic market success. The exact characteristics of the programmatic support should be developed based on inputs from both supplier and user stakeholders.

If material is not available from foreign sources, government support of procurement of HALEU from alternative near-term sources will be needed to support the successful completion of the ARDP projects. Identification of specific material sources and quantification of material production costs must be aligned

[4] Federal Register: Request for Information (RFI) Regarding Planning for Establishment of a Program To Support the Availability of High-Assay Low-Enriched Uranium (HALEU) for Civilian Domestic Research, Development, Demonstration, and Commercial Use

with DOE prioritization of material allocations for DOE-NE and DOE-NNSA projects. Accelerated alignment within DOE on these questions of material availability and prioritization would be critical to meeting near-term HALEU needs.

### Mid-term HALEU production infrastructure investment program

The third element of the market development program is the mid-term HALEU production infrastructure investment program. Example supply-side programmatic goals for this element of the program could include:

- Multiple viable suppliers with substantial HALEU production capacity (e.g., > 10 MTU of HALEU per year per supplier) are capable of providing both enrichment and deconversion services
- Suppliers are capable of subsequent expansions of HALEU enrichment and deconversion capabilities within a reasonable timeframe (e.g., within 4 years of confirmed project funding).
- Specific quantitative goals for this element of the program would need to be defined to ensure that the supply-side program satisfies demand-side constraints. These quantitative goals should be based on input from HALEU users to ensure they meet overall programmatic goals. Example quantitative goals could include targeted total domestic commercial HALEU production capacity in a general physical form and enrichment by 2028. The target production capacity could be based on DOE programmatic review and validation of user demand predictions and supplier capabilities.
- Development and deployment of fuel cycle infrastructure to integrate with new or existing transportation and fuel fabrication infrastructure is sufficient based on DOE programmatic review of fuel cycle integration.

A supplier-focused proposal bid program (along with detailed input from HALEU users) could be used to support this activity. The mid-term HALEU production infrastructure investment program could solicit competitive bids for different HALEU production infrastructure investments. DOE could then select, on a cost-competitive basis, the set of proposed infrastructure investments that best meet the specific programmatic requirements.

The overall activity costs and liability would be set based on the total funding available. Three metrics would be considered for each activity proposal:

1. Total appropriations needed (e.g., total cost of off-take material purchases or federal share of cost-share support as well as the total cost associated with any difference between average procurement price from an off-take agreement and the average resale price),
2. Maximum program liability (i.e., the total cost of the guaranteed off-take material purchases, costs resulting from off-take buy-outs, costs resulting from storage or leasing storage of off-taken HALEU, and federal cost-share), and
3. Minimum program liability (i.e., total program costs assuming full cost recovery of off-take material purchases and federal share of cost-share support).

The first cost quantifies the total funding level needed to support activities absent any cost-recovery activities and completion of all off-take agreements. The second cost quantifies the maximum taxpayer liability to support activities absent any cost-recovery activities and use of off-take buy-out options. The third cost quantifies the minimum taxpayer liability if cost-recovery activities associated with off-take

material purchases are successfully completed. These three costs represent the total, maximum, and minimum costs associated with different program options.

Table 1 provides example implementations to highlight the impact of the different policy mechanisms on the three cost metrics in nominal 2022 USD. Note that the parameters presented in Table 1 could be changed and reevaluated to enable comparison of alternative policy mechanisms.

The example policy mechanisms in Table 1 demonstrates how different policy mechanisms could be utilized by suppliers to support a variety of HALEU infrastructure investment business cases as well as the different appropriation and liability implications of the three mechanisms. Off-take agreements require significant appropriations (absent crediting cost-recovery from material sales to reduce appropriation needs) but may have a minimal overall tax-payer liability if the program can implement sale of off-take material to end users at or near procurement cost. Cost-share agreements may require lower total appropriations but have a significant fixed tax-payer liability due to the absence of cost-recovery mechanisms. Combined cost-share and partial off-take agreements could be tailored to balance the appropriation requirements and potential for cost-recovery through material sale. Input from prospective suppliers will be needed to determine the extent to which different structures would support investments in production. If the program design to do so is feasible, the specific conditions for each policy mechanism could be developed by the suppliers to meet their business objective by proposing different agreement characteristics that satisfy overall programmatic goals and funding requirements.

**The examples presented below in Table 1 are simply illustrations of potential program design. The three policy mechanisms should not be considered as developing equivalent production capabilities.**

Table 1. Example HALEU infrastructure support policy mechanisms

| *Agreement Characteristics* | *Off-take Agreement* | *Cost-share Agreement* | *Cost-share with Partial Off-take Agreement* |
|---|---|---|---|
| Production Capacity (MTU/y) | 10 | 10 | 10 |
| Cost Share (Public to Private) | N/A | 50:50 | 50:50 |
| Capital Cost | N/A | $500,000,000 | $125,000,000 |
| Capital Liability | N/A | $250,000,000 | $96,000,000 |
| Off-take Price ($/kgU) | $15,000 | N/A | $15,000 |
| Off-take Quantity (MTU/y) | 10 | N/A | 5 |
| Off-take Duration (y) | 10 | N/A | 5 |
| Annual Off-take Costs | $150,000,000 | N/A | $75,000,000 |
| Off-take Total Costs [Note 1] | $1,500,000,000 | N/A | $375,000,000 |
| Years of Off-take Duration Eligible for Buy-out (y) | 5 | N/A | 5 |
| Off-take Buy-out Percentage | 40% | N/A | 40% |
| Off-take Buy-out Liability [Note 2] | $300,000,000 | N/A | $150,000,000 |
| Total Appropriations Needed (Capital costs, off-take total costs) | $1,500,000,000 | $250,000,000 | $500,000,000 |
| Maximum Program Liability (Capital costs, stranded off-take liability, off-take buy-out liability) [Note 3] | $1,050,000,000 | $250,000,000 | $275,000,000 |
| Minimum Program Liability (Capital costs) [Note 4] | $0 | $250,000,000 | $125,000,000 |

Note 1: Off-take costs do not include the costs associated with transportation or storage of off-take material. These costs would be vary depending on the quantity, form, duration, and liability of material storage as well as the ability to utilize existing infrastructure or the need to construct new infrastructure. This number could be calculated by a standard contracting process by the program or provided as a part of a project proposal.

Note 2: Off-take buy-out liability is calculated based on product of off-take quantity, off-take price, years of off-take duration eligible for buy-out, and off-take buy-out percentage. This number could be calculated by a standard metric or provided as a part of a project proposal.

Note 3: Maximum program liability assumes no sale of off-take material and program ownership or liability for all off-taken material, exercise of off-take buy-out at full liability, and program capital liability.

Note 4: Minimum program liability assumes that all off-take material is sold at cost with revenue returned to the federal government with program capital liability as the only major remaining liability.

Each of these three policy mechanisms could also be extended to other physical infrastructure needed to support fuel cycle development and deployment, including infrastructure needed to integrate with new or existing transportation and fuel fabrication infrastructure. Applicants (including enrichment companies, fuel manufacturers, transportation providers, or other nuclear service providers) could propose different funding scenarios to support infrastructure investment such as new deconversion facilities or new transportation infrastructure. Additional metrics related to off-take (e.g., cost per MTU of conversion capability) would be needed to enable use of any of the support scenarios. The societal benefits of utilizing existing fuel cycle sites and facilities versus new HALEU fuel cycle physical infrastructure should be evaluated when assessing proposals. The environmental and social justice impacts of new versus existing infrastructure should also be evaluated, particularly considering the significant historical impacts of fuel cycle and nuclear material activities in the United States.

A milestones-based approach should be applied to help reduce project funding risk for any approach to a mid-term HALEU market development. Standardized milestones could be established for each type of policy mechanism by the DOE project offices or created by a supplier on a proposal-by-proposal basis depending on their specific project needs. Example milestones for a cost-share agreement could include:

- Submission of project and applicant details or overall project plan
- Approval of facility operating licenses by the Nuclear Regulatory Commission
- Commitment of financing (sometimes referenced as “Financial Closing”)
- Installation of key components throughout construction
- Facility completion, commissioning, and first production of HALEU (and associated forms)
- Demonstration of HALEU production
- Demonstration of HALEU sale at a cost-competitive price

Like the establishment of milestones, the allocation of program support across different milestones could be based on a standard schedule or negotiated and approved individually for each proposal. Holistic program evaluation of multiple different HALEU production infrastructure investment proposals could help smooth out annual program spending over the length of the program.

### Mid-term HALEU supply resale program

The fourth commercial HALEU market development program activity is the HALEU resale program. The supply and demand side programmatic goals for this element of the program are:

- Providing ongoing market assurance of HALEU demand based on supply from off-take agreements
- Maintaining a small held HALEU inventory from off-take agreements or other mechanisms to provide ongoing market assurance of HALEU supply

Specific quantitative goals for this element of the program would need to be defined to ensure that this element of the program meets supply and demand side constraints. These quantitative goals should be based on input from HALEU suppliers and users to ensure they meet overall programmatic goals. Example quantitative goals could include:

- Specify a cost recovery target to enable program reinvestment and minimize taxpayer losses on off-take material purchases

- Maintain a minimum price for the sale of inventory, based on procurement cost, to avoid market disruptions

The HALEU resale program will only occur as part of a HALEU market development program if off-take agreements are provided to HALEU suppliers. This program allows for the resale of HALEU to material end users. Some market slack (and the resulting build-up of unsold inventory) is desirable to maintain user supply assurance, but excessive build-up of held inventory would indicate that the program parameters need to be adjusted.

Four major factors must be considered when developing a HALEU resale program:

1. market rules for purchase and sale,
2. cost recovery formulas,
3. quantity of material held for sale by DOE, and
4. price competition effects.

First, the market rules for sale could include under what market conditions material may be sold, and how sales are bid or HALEU buyers are selected. The market rules could be designed to allow for the program to offer future contracts on the committed purchases and directly facilitate purchases with a supplier. Off-take material not sold using these future contracts could be sold by the program on an open market.

Second, cost recovery formulas establish how prices are set for sale of material on the secondary market, including what fraction of the initial purchase cost should be recovered by the sale and whether additional funds should be recovered by the sale to fund program administrative costs. Full cost recovery based on purchase price or open auction represent two simplified methods for setting cost absent other factors.

Third, quantity of material held for sale by DOE is the amount of material retained by the DOE to provide ongoing market assurance of HALEU supply. While large target held material inventories facilitate significant purchasing activities, assurance of material availability, and reduction in market fluctuations, they are a significant liability both in terms of program funding liquidity, storage construction, operation, leasing, and maintenance costs, as well as stranded assets if HALEU cannot be resold at cost. Instead, a smaller target held material inventory could be used to ensure material availability for demonstration and development activities or to reduce the impacts of potential fuel cycle disruptions or delays on market maturation. However, even a smaller target held material inventory would still carry storage liability so the financial implications of this inventory must be assessed.

It is important to note that if demand for HALEU does not materialize after the DOE has purchased significant quantities of HALEU, material may continue to accumulate in program stockpiles. The continued accumulation without clear signals for future demand would likely reflect a lack of advanced reactor deployment. Policymakers must have clear criteria for terminating off-take agreements and exercising buyout provisions to limit taxpayer liability. The criteria for these decisions should be clearly defined and communicated with stakeholders to provide market transparency and facilitate clarity in business decisions.

Fourth, potential price competition must be factored in when developing a HALEU resale program. Market competition for HALEU fuel cycle activities may develop from international HALEU suppliers or from other domestic supplies that are not part of the market development program. If the off-take price for HALEU is significantly higher than the market price, it may not be possible for the program to sell the material at

cost. If the market cost of HALEU is significantly lower than the cost of HALEU procurement in the near term and demand is not expected to increase, policymakers must have clear criteria for changing program operation and reducing program losses or excess material accumulation. Potential responses could include terminating off-take agreements and exercising buyout provisions to limit taxpayer liability or offering material for sale or transfer to other government programs (e.g., NNSA, DOD, NASA) not initially included in the HALEU market development program. The criteria for these decisions should be clearly defined and communicated with stakeholders to provide market transparency and facilitate certainty in business decisions. Other potential responses to inadequate market conditions, such as selling material at below procurement prices to eliminate on-going storage costs, should be carefully evaluated to ensure that it does not cause inadvertent harm to commercial uranium fuel markets.

## Role of government in HALEU fuel cycle development

The federal government has a unique opportunity to help catalyze a domestic commercial HALEU fuel cycle market. The ability to provide both short-term demand and supply assurances using federal funding and purchasing power can provide the necessary momentum to attract private investment and development of domestic commercial HALEU fuel cycle activities. This white paper describes several policy mechanisms the government could utilize to facilitate market development. The role of the federal government is to catalyze development of a sustainable, mature, commercial market and the following principles should be emphasized when designing a program:

- *Urgency* – Development of new HALEU infrastructure may take more than 4 years following confirmation of project funding with an additional 2 years required for the production and fabrication of HALEU fuels for advanced reactors. Meeting national advanced reactor development goals in the late 2020s, therefore, requires government to quickly establish and stand up programs that can support HALEU fuel cycle infrastructure investment. The government must move quickly to match the pace of advanced reactor development.
- *Priority* – The government is poised to invest billions of dollars in advanced reactor demonstration. Developing commercial HALEU markets and providing fuel for these reactors is essential. The government must prioritize management of HALEU fuel cycle development activities to facilitate successful completion of advanced reactor projects.
- *Competition* – Government support can provide unparalleled stability to developing markets, but it is critical that the domestic commercial HALEU fuel cycle market be able to sustain operations following program completion. Use of competitive bid contracts, sales and purchase agreements, and a focus on funding robust projects through milestone-based agreements are critical to ensuring that continued government support is not required to sustain long-term commercial HALEU fuel cycle activities.

Government-led programs should incorporate these principles to help ensure the commercial HALEU market development program successfully helps catalyze activities in a timeframe necessary to support national goals for advanced reactor commercialization while effectively and judiciously using government funding.

## Role of industry in HALEU fuel cycle development

Active participation by private industry as well as the government is critical to the successful development of a domestic commercial HALEU fuel cycle market. Both potential HALEU suppliers and HALEU users are needed to catalyze market development. The following activities should be prioritized by industry to help facilitate market development:

- *Business consortiums* – Inadequate demand signals for HALEU are a key factor inhibiting the development of a commercial HALEU fuel cycle market. The uncertainty related to the HALEU demand associated with an individual company, facility, or project are significant, so companies may be unwilling to make significant commercial investments to provide supply. Additionally, the expected HALEU fuel cycle costs are sufficiently high that individual companies may be unable or unwilling to provide forward funding. Industry self-organization of business consortiums for shared infrastructure or demand could help reduce the risks to individual companies by leveraging the successful development or deployment of any one member. Industry should seek to develop these markets independent of government programs and help provide additional supply or demand signals that support market development.
- *Prioritization of program activities* – Industry is best positioned to identify the key specific activities or facilities that limit the development of a domestic commercial HALEU fuel cycle market. Industry participants should regularly coordinate to identify limiting activities and communicate to policymakers what activities a commercial HALEU market development program should prioritize to support private investment most effectively. The full scope of the HALEU fuel cycle from mining through fuel fabrication should be reviewed to help ensure overall development of a robust commercial HALEU market.
- *Transparency in market development program participation* – Industry should provide complete and accurate information to maximize the likelihood of commercial HALEU market development. Industry submittal of low-confidence estimates of HALEU demand, timeline, or cost to a HALEU market development program damages the ability of the commercial HALEU market development program to create policy mechanisms with a high probability of success. To encourage complete and accurate reporting, DOE must design commercial HALEU market consortium programs with adequate safeguards to protect sensitive business information provided by industry.

Industry prioritization of these activities could have significant synergistic effects with a federal program and help catalyze the more rapid development of a mature domestic commercial HALEU fuel cycle market.

# Conclusions

Development of a reliable and commercially viable HALEU fuel cycle is critical to the successful deployment of many advanced reactor technologies as an energy and climate solution.

Global supply of HALEU is currently dominated by a single company: the Russian state-owned enterprise TENEX. Reliance of future advanced reactor HALEU fuel cycles on a single, state-owned company creates significant economic and political risks. The February 2022 Russian invasion of Ukraine and the resulting geopolitical and commercial uncertainty was a stark warning against the overreliance on TENEX as a short-term or long-term fuel cycle partner for advanced reactor development projects. A diverse, reliable, and commercially viable HALEU fuel cycle is essential for the successful deployment of advanced reactors.

The absence of market signals to develop new domestic HALEU supply and enable long-term HALEU demand has contributed to limited deployment of new HALEU fuel cycle infrastructure. Despite significant government and private investments in advanced reactor technology development, additional assurance of long-term commercial demand and assurance of long-term commercial supply of HALEU are needed to spur private investment in the HALEU fuel cycle. A commercial HALEU market development program would enable the federal government to catalyze development of domestic markets and support advanced reactor commercialization goals.

A new commercial HALEU market development program should focus on creating the near-term and mid-term supply and demand signals to help facilitate long-term market development and maturation. Commercial HALEU market development program support should include all aspects of the HALEU fuel cycle including enrichment facilities, transportation infrastructure, and conversion/deconversion facilities. Program-level identification of possible supply chain bottlenecks that will not be appropriately resolved by market supply and demand signals should be used to formulate federal market development programs and help catalyze a robust commercial HALEU fuel cycle.

Review of market conditions and policymaking considerations will affect specific programmatic design considerations, but a commercial development program should include the following major activities:

- Evaluation of near-term and long-term need for domestic HALEU fuel cycle activities depending on deployment of advanced reactors and availability of HALEU from international markets.
- Facilitation of near-term procurement of HALEU by providing programmatic support for HALEU procurement by end users.
- Support (financial and programmatic) of supplier investments in new HALEU fuel cycle production and fuel-cycle infrastructure through either off-take procurement contracts or cost-share agreements to support mid-term market availability of HALEU or a combination of off-take contracts and cost-share agreements.
- Facilitation of resale? of HALEU production purchased by the federal government under off-take agreements to provide additional mid-term HALEU supply assurance.

These activities help meet the overall goals of a commercial HALEU cycle development program for both HALEU suppliers and users. Federal HALEU fuel cycle market development programs can be designed to meet the needs of different HALEU fuel cycle companies while providing the supply and demand assurances needed to support the successful commercialization of advanced reactors as a climate solution.