Characterizing an Emerging Market for High-Assay Low-Enriched Uranium Production

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Characterizing an Emerging Market for High-Assay, Low-Enriched Uranium Production:

HALEU Production Cost Analysis and Market Program Evaluation

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Executive Summary

Ensuring a reliable and robust commercial supply of high-assay, low-enriched uranium (HALEU) fuel is critical to the successful commercialization and deployment of many advanced reactor designs. Commercial HALEU is currently only available from the Russian state-owned company TENEX, posing a significant commercial risk for advanced reactor projects that require HALEU. Catalyzing domestic commercial production of HALEU will reduce U.S. dependence on supply chains that are subject to international geopolitical and economic disruptions, enable the successful deployment of advanced nuclear energy as a clean energy solution, and create a reliable domestic source of advanced reactor fuel to support global export of U.S. nuclear energy technologies.

Despite stakeholder agreement that a domestic commercial HALEU market and fuel cycle is needed, and recent action by Congress, the Department of Energy, and private companies to address the HALEU fuel cycle challenges, there has been limited public discussion on the market challenges of effectively incentivizing private investment in new HALEU production capacity. Specifically, while high-level estimated costs of HALEU production and funding requirements for a federal program to catalyze investment in new HALEU production capacity are adequate for program establishment, more detailed and robust characterization of costs and funding requirements is needed for program implementation. This report fills this need by characterizing and quantifying HALEU production costs and analyzing two different types of HALEU availability programs. These analyses provide a common basis for discussion between advanced reactor companies, fuel cycle service providers, fuel end users, and policymakers on the programmatic needs to catalyze new domestic commercial production of HALEU.

The HALEU production cost model developed in this report provides five key insights on the cost challenges associated with HALEU production:

- Expected HALEU production cost for uranium enriched to 19.75% is $23,725 / kgU for HALEU in an oxide form and $25,725 for HALEU in a metallic form under baseline economic assumptions but could be higher based on specific process cost drivers. Approximately 65% of the HALEU production costs are driven by existing commercial LEU fuel cycle activities (including uranium mining, uranium conversion, and LEU enrichment). The commodity costs and market dynamics associated with these LEU fuel cycle activities must be considered when assessing HALEU production cost. The remaining 35% of HALEU production costs are driven by new HALEU production activities (including HALEU enrichment and deconversion). These costs may vary significantly based on the scale of HALEU production capacity and economic assumptions around facility operation and payback periods. Longer and larger guaranteed contracts enable both lower short-term and long-term production costs for new HALEU production facilities.
- The cost of producing HALEU will depend significantly on existing uranium market dynamics including the commodity price of uranium, commercial uranium conversion service costs, and commercial low enriched uranium (LEU) enrichment (used as feedstock for HALEU enrichment). These activities represent 65% of the total HALEU production costs in the baseline cost analysis in this report. These costs will vary based on existing global uranium market dynamics for LEU fuel production. It is important that long-term HALEU production contracts account for variable LEU fuel cycle commodity prices (or mitigate risk through long-term contracts) to reduce price volatility and ensure production.

- Significant HALEU production (on the order of hundreds of metric tons of uranium [MTU] per year) would likely be required before the demands associated with HALEU production would make a substantive impact on existing global uranium markets. While the LEU enrichment capacity required to support near-term HALEU production of 25 MTU per year (916 thousand separative work units [kSWU] per year) is small compared to Western nation enrichment capacity (26,000 kSWU per year), it is approximately 20% of existing U.S. enrichment capacity (4,900 kSWU per year). The effect of HALEU production on LEU fuel cycle markets for existing reactors may be substantial if the global enrichment market is heavily constrained due to higher demand or international uranium trade restrictions, resulting in limited excess LEU production capacity.
- A majority of the uranium enrichment required to produce HALEU can be completed in existing LEU fuel cycle facilities. Producing a kilogram of HALEU at 19.75% enrichment requires 36.63 separative work units (SWU) of LEU enrichment (0.7% U-235 to 5% U-235) and 5.89 SWU of HALEU enrichment (5% U-235 to 19.75% U-235). Performing LEU enrichment at existing or expanded LEU enrichment facilities minimizes the enrichment work performed at new HALEU enrichment facilities that will have higher enrichment costs due to design, licensing, construction, and regulatory requirements for new HALEU facilities. Separating LEU and HALEU enrichment for HALEU production maximizes output (MTU/year) and minimizes costs ($/kgU).
- The near-term costs of HALEU deconversion may be large ($2,000/kgU for oxide deconversion and $4,000/kgU for metallic deconversion), but will depend significantly on economies of scale associated with construction and operation of small deconversion facilities. The costs for metallic deconversion are expected to much higher than for oxide deconversion since there are no existing commercial facilities in the United States that perform metallic deconversion at scale. The long-term costs of HALEU deconversion may decrease as HALEU production increases, the capital costs of new production facilities are fully amortized, and there is increased experience with HALEU deconversion processes to oxide and metallic forms.

Two different HALEU production support programs are evaluated in this paper: a HALEU “material off-take agreement” program and a HALEU “production services agreement” program. The evaluation of these two programs in this report provides four key insights regarding the cost and operational challenges associated with each:

- The first programmatic option is the guaranteed government purchase and sale of HALEU through a material off-take agreement program that can be designed to incentivize private investment in new commercial HALEU production. The program can minimize taxpayer burden while supporting new HALEU production capacity, but requires substantial program funding and management to successfully operate based on the range of possible HALEU cost, demand, and supply scenarios:
    - Total up-front appropriations of $6.3 billion to $7.2 billion for a HALEU material off-take agreement program would enable successful operation of the program under a wide variety of market scenarios to catalyze a domestic commercial HALEU market. Smaller total up-front appropriations of $1.5 billion to $2.9 billion for the HALEU material off-take agreement program could enable program operation but may require additional appropriations if market conditions diverge significantly from the expected HALEU production costs or industry HALEU demand.[1]

[1] The HALEU material off-take agreement program appropriations requirements are consistent with the HALEU portion of the combined LEU-HALEU program appropriations using a revolving fund described in NIA’s June 2023 paper "Additional Flexible Funding is Needed to Break Dependence on Russian Nuclear Fuel"

- The majority of the program funding required for a HALEU material off-take agreement program is spent on procuring LEU feed material from existing LEU fuel cycle markets as opposed to building or operating HALEU enrichment facilities. Approximately 65% of the total HALEU production costs are due to uranium mining, conversion and LEU enrichment costs, so material off-take agreements will directly support purchases from LEU markets. This also makes the appropriation requirements for the HALEU material off-take agreement program sensitive to LEU fuel cycle commodity prices.
- Enabling the use of a "revolving fund" (permitting revenue from prior program HALEU sales to directly fund future HALEU purchase) is extremely effective at reducing the total appropriations requirements for a HALEU material off-take agreement program, reducing the total appropriations requirements by 75% - 80% under baseline assumptions. The reduced up-front appropriations burden can significantly reduce challenges associated with securing the appropriations necessary to support program activities. The net program expenditures will be the same whether or not a revolving fund is used, unless the revolving fund itself is managed to enable efficiencies.
- Enabling an option for a "negotiated contract buy-out" can significantly reduce the appropriations requirements and government financial liabilities associated with large HALEU inventories that may result if commercial demand does not materialize as expected. Use of a negotiated contract buy-out effectively limits program costs and financial liabilities under worst case HALEU market demand conditions and protects taxpayers. This option for a negotiated contract buy-out is required to effectively use a revolving fund to reduce up-front appropriations requirements.

- The second programmatic option is guaranteed government procurement of HALEU production services (HALEU enrichment, deconversion, and transportation) through HALEU production services agreements. This program can focus government support on catalyzing investment in new commercial HALEU production activities that do not currently have reliable supply and demand signals:
  - Total up-front appropriations of $2 billion for a HALEU production services agreement program would enable successful operation of the program and would help catalyze investment in domestic HALEU production facilities. The program can recover costs over time through the sale or transfer of HALEU enrichment, deconversion, or other production service contracts to private companies or other federal customers. The program would also have the option to produce HALEU for a government stockpile using the production service contracts but additional future appropriations would be necessary to acquire the required LEU feedstock material from existing LEU commodity markets.
  - The HALEU production services agreement program reduces the long-term financial risk for both companies and the federal government. HALEU production companies do not need to hedge against long-term commodity prices if setting fixed prices for HALEU production as part of a material off-take agreement and the federal appropriators do not need to account for LEU fuel cycle price volatility when allocating funding to a material off-take agreement that may use an escalating or cost-plus contract structure for HALEU production. This helps reduce the risk of program failure due to insufficient funds.
  - The HALEU production services agreement program focuses federal investment towards new HALEU production capacity. The HALEU production service agreements are entirely focused on activities that require new facilities or operations (HALEU enrichment, deconversion, and transportation). The program more effectively supports new production capacity rather than procuring LEU feed material from existing LEU fuel cycle

markets. The program also provides guaranteed payment over a multi-year period for new HALEU production services, enabling private companies to secure capital funding critical to design, license, construct, and commission new HALEU production facilities.

  - New legislative authorization may be required to enable use of service agreements to catalyze HALEU production. The authorizing legislation for the Department of Energy HALEU Availability Program in the Energy Act of 2020 requires the federal government to "acquire and provide" HALEU for commercial advanced reactor companies to help catalyze new domestic HALEU production but it is not clear whether use of service contracts to catalyze new domestic HALEU production would be permitted. New legislative authorization may be required to allow DOE to use this program structure to support development of new domestic HALEU production capacity.

- Both programmatic options to catalyze investment in new commercial HALEU production activities require significant increases in upfront appropriation to support successful operations. The new private capital investments required to design, license, construct, and commission new HALEU production facilities require commercial assurance of return. Upfront appropriations guarantee the availability of program funds and reduce commercial risk associated with reliance on the annual appropriations process. Significant increases in federal appropriations (in addition to the $700 million provided for HALEU programs in the 2022 Inflation Reduction Act) are required to support successful program operation and catalyze investment in new commercial, domestic HALEU production.

The HALEU production cost model and evaluations of HALEU availability programs in this report are not intended to provide definitive quantification of the costs associated with HALEU. Instead, the methods described here are intended as a transparent basis for discussions between advanced reactor companies, fuel cycle service providers, fuel end users, and policymakers on the needs to catalyze domestic commercial production of HALEU.

Solving the "chicken-and-the-egg" problem associated with misaligned HALEU market supply and demand signals can be accomplished using federal government support. Clear understanding of private commercial requirements, public funding constraints, and operational uncertainty is critical to creating a robust program that catalyzes private investment in the HALEU fuel cycle and leads to a sustainable domestic market for HALEU.

1 Introduction

Advanced nuclear reactors that utilize advanced High-Assay Low-Enriched Uranium (HALEU) fuels have emerged as a promising technological innovation in the global pursuit of clean, sustainable, and reliable power generation. As the United States navigates the complexities of transitioning to a cleaner and more sustainable energy system, understanding the role of HALEU is essential for envisioning a world powered by clean and reliable advanced nuclear energy.

HALEU possesses a higher concentration of the fissile isotope uranium-235 than conventional low-enriched uranium (LEU). Conventional LEU fuels typically have a uranium-235 enrichment of less than 5% while HALEU fuels typically have a uranium-235 enrichment greater than 10% and less than 20%. This higher enrichment may offer advanced reactors that use this fuel form several advantages, including greater fuel efficiency, improved safety characteristics, or reduced proliferation risks. Therefore, HALEU has a pivotal role in unlocking the full potential of advanced nuclear reactor technologies. In order to ensure the successful deployment of these advanced reactors, access to a stable and economically viable supply of HALEU is key.

Currently, there is no commercially available source of HALEU within the United States. The only commercial producer of HALEU globally is the Russian state-owned enterprise TENEX, which is no longer a viable trade partner after the February 2022 Russian invasion of Ukraine. Between 2018 and 2022, U.S. companies relied on TENEX to provide 24% of all LEU enrichment services for existing reactors. Figure 1 shows the percentage of domestic nuclear fuel enrichment services provided to the United States by country in 2022.

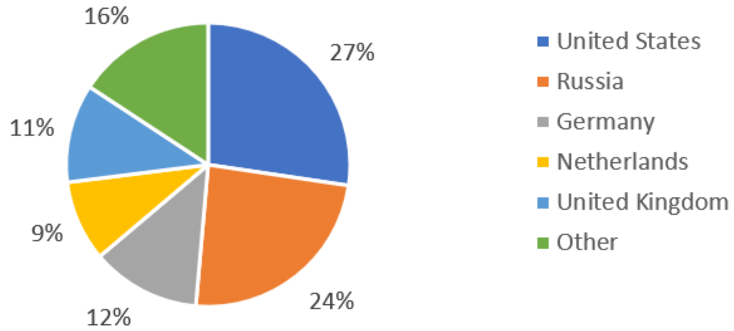

Figure 1. Current U.S. reliance on different countries for enrichment to meet domestic nuclear fuel needs[2]

Relying on TENEX for HALEU for advanced reactors is unsustainable and limits the United States' ability to successfully develop and deploy advanced reactors domestically and abroad. Establishing a U.S.-based supply chain to produce HALEU is crucial for insulating the United States from geopolitical and economic issues abroad, reducing our dependence on unreliable foreign sources, and ensuring the successful deployment of advanced nuclear energy.

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[2] EIA | 2022 Uranium Marketing Annual Report

Many of the advanced reactor technologies that are scheduled to be deployed in the next decade by private companies and supported through public-private partnerships will require HALEU.[3] Nine out of the ten reactor designs funded as part of the multi-billion-dollar government Advanced Reactor Demonstration Program (ARDP) will require HALEU. While some first-of-a-kind (FOAK) advanced reactors will obtain limited quantities of HALEU from special government programs (specifically from limited HALEU stockpiles made available by the U.S. national laboratories), this pathway is not available for all advanced reactor technologies and is not commercially viable in the long term. It is not clear where other advanced reactors will obtain their initial fuel cores, unless construction of new domestic HALEU production capacity begins very soon. Establishing a domestic HALEU supply is critical to safeguarding the significant financial commitment the government has already made to the ARDP.

Some advanced reactor developers without clear lines of sight on HALEU for their FOAK reactor cores are already having to delay construction due to insufficient amounts of commercially available HALEU.[4] HALEU supply for second-of-a-kind and subsequent reactors is even more uncertain. This uncertainty, if left unaddressed, has the potential to leave future advanced reactors without fuel, creating a ripple effect that can not only inhibit near-term deployments but also undermine the prospects for more widespread long-term adoption of advanced nuclear technologies. Without a sustainable HALEU supply, it is unlikely that this substantial public investment in technology demonstrations and development activities will catalyze the deployment of new advanced reactors at scale in the 2030s. These delays in the deployment of advanced nuclear reactors caused by HALEU supply limitations will hinder progress towards achieving near- and long-term decarbonization goals and impede the transition to a low-carbon future using advanced nuclear energy.

Additionally, ensuring a domestic HALEU supply chain is also essential to establishing a competitive advantage for U.S. advanced reactor developers on the international stage. There is growing interest internationally to deploy advanced nuclear reactors, particularly advanced reactor designs that require HALEU. The United States must be able to provide the fuel required for these reactors or risk conceding the fuel market to other countries, predominantly Russia or China. Conceding market control to Russia or China in this area not only jeopardizes the United States' competitive advantage but also hinders the implementation of robust safeguard and security regimes, compromising our ability to ensure the safe and responsible utilization of advanced nuclear technologies internationally. Failing to lead internationally in any of these areas would hinder the United States' aspiration to be a global leader in generating clean, advanced nuclear energy and inhibit U.S. efforts to strengthen safety, security, and nonproliferation norms around the world. Therefore, becoming a leading supplier of HALEU establishes a competitive edge by positioning the United States at the forefront of the global stage, ensuring energy security, and maintaining a pivotal role in shaping the future of advanced nuclear technologies.

Ensuring a long-term reliable supply of HALEU for advanced reactors and maintaining a competitive advantage in future HALEU markets requires additional domestic capacity to produce HALEU. This domestic capacity must be developed swiftly to support future advanced reactor deployments given the public and private investment in HALEU-dependent advanced reactor technologies, and the energy security, international security, and climate benefits of advanced reactor deployment.

[3] NIA | Advanced Reactor Deployment Timelines
[4] WNN | HALEU Fuel Availability Delays Natrium Reactor Project

1.1 HALEU Fuel Supply Chain Description

The barriers to establishing a new domestic HALEU fuel supply chain can be characterized by the different commercial activities and processes required to produce HALEU fuels. The HALEU production process (prior to reactor technology-specific fuel fabrication[5]) can be characterized by the following four stages:

1. Mining: Mining and processing uranium to produce an intermediate solid uranium oxide (typically U_3O_8 or "yellowcake") through physical and chemical processes. This includes open-pit and underground uranium ore mining, milling, and processing methods as well as in-situ leaching and in-situ recovery mining and processing methods.
2. Conversion: Converting solid uranium oxide products into uranium hexafluoride (UF_6) through chemical processes. UF_6 is gaseous at room pressure (1 atm) at temperatures above 64°C and is suitable for gaseous enrichment processes.
3. Enrichment: Gradually increasing the isotopic concentration of Uranium-235 in gaseous uranium (UF_6) through physical processing.
4. Deconversion: Converting gaseous enriched uranium into a solid uranium form through chemical processing. The typical solid forms are uranium oxide (UO_2) or metallic uranium (U).

It is important to note the mining, conversion, and enrichment stages (up to 5% U-235) are common for both LEU and HALEU fuel cycle production. Additionally, each of these process stages may be connected by transportation based on the location or co-location of the activities and facilities. For example, deconversion and fuel fabrication activities are typically collocated and vertically integrated by fuel manufacturers for the current LEU fuel cycle, but it is possible that the future HALEU fuel cycle may evolve differently, for example with enrichment and deconversion collocated based on deconversion facility or material transportation constraints and costs.

Figure 2 illustrates the commercial fuel cycle services required to deliver LEU fuel as a commercial fuel product, as well as the new facilities and infrastructure required to produce HALEU fuel for advanced reactor owners and operators.

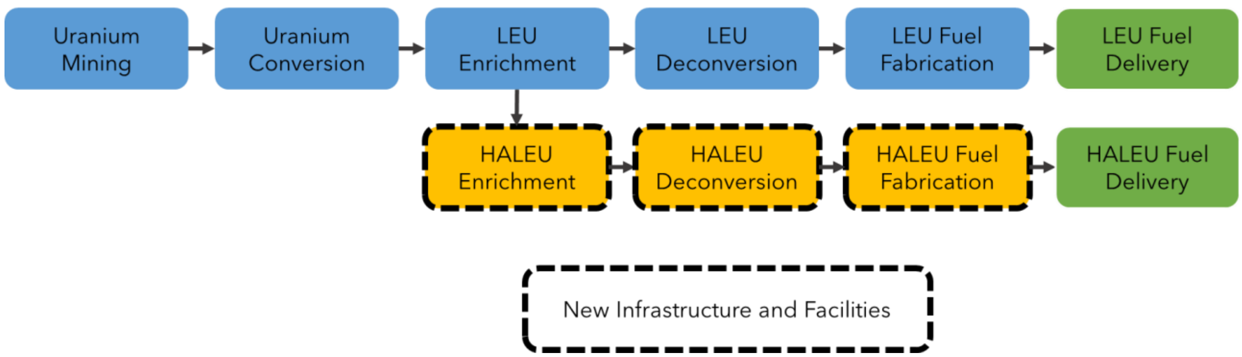

Figure 2. The LEU fuel cycle and the HALEU fuel cycle challenge

[5] Fabrication refers to the manufacturing process of converting deconverted uranium into fuel suitable for use in nuclear reactors, such as uranium oxide fuel pellets, metallic uranium fuel elements, or TRISO (Tri-structural Isotropic) fuel particles.

The major supply chain challenge with creating new HALEU production capacity is that it requires the development of new fuel cycle infrastructure and facilities, specifically HALEU enrichment capacity[6], HALEU deconversion capacity[7], and HALEU fuel fabrication facilities[8]. Additionally, the HALEU fuel supply chain will require new transportation infrastructure between supply chain steps that can accommodate higher-enriched uranium products and fuel than are currently available commercially. The required new supply chain infrastructure and facilities are described briefly below:

- HALEU enrichment: deployment of new uranium enrichment facilities that can accommodate enrichments up to 19.75% U-235. While these facilities will use the same fundamental enrichment technology as LEU enrichment facilities, they will have additional design, operational, security, and safeguard constraints due to the higher enrichment. LEU enrichment facilities are commercially mature operations in the United States, but there is less recent experience[9] with HALEU enrichment facilities. Investment in new facilities will be required.
- HALEU deconversion: deployment of new uranium deconversion facilities that can accommodate enrichments up to 19.75% U-235. These facilities may need to convert UF_6 into an oxide form (typically UO_2) or into a metallic form (U) based on the requirements of fuel fabricators or end customers.[10] Uranium deconversion to an oxide form is a commercially mature process (already available for LEU fuel cycle activities) but new facilities would need to be designed to handle higher enrichment. Uranium deconversion to a metallic form is not yet commercially mature and could require additional development activities to implement at scale. Uranium deconversion to metallic forms in the near term would likely first require deconversion to an oxide form and then subsequent reconversion into a metallic form. Investment in new deconversion facilities will be required.
- HALEU fuel fabrication: deployment of new fuel production facilities that can create the specific fuel forms needed for advanced reactors. These facilities will be operated as part of the design-specific supply chain for an individual advanced reactor developer and new reactor project. These facilities cannot be generically characterized and are thus not further analyzed in this report. The remainder of this report will specifically discuss the costs and challenges associated with HALEU material production (excluding fuel fabrication) and not HALEU fuel production. This distinction means that the cost and policy recommendations in this report do not consider the impact of technology-specific fuel fabrication infrastructure, facilities, and processes.

Creating domestic HALEU supply chain requires significant private investment to design, license, construct and operate new supply chain infrastructure and facilities. Private investment in the deployment of HALEU-specific infrastructure and facilities is required to establish a long-term reliable supply of HALEU for advanced reactors in the United States.

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[6] Enrichment involves increasing the concentration of the uranium-235 isotope in uranium.
[7] Deconversion is the process of converting enriched uranium hexafluoride (UF_6) used in the uranium enrichment process back into a more stable and less reactive form, either an oxide or metallic form, that can be used in the fabrication processes.
[8] Fabrication refers to the manufacturing process of converting deconverted uranium into fuel suitable for use in nuclear reactors, such as uranium oxide fuel pellets, metallic uranium fuel elements, or TRISO (Tri-structural Isotropic) fuel particles.
[9] Recent domestic HALEU enrichment is limited to Centrus Energy Corp's enrichment facility in Piketon Ohio: DOE | Centrus Produces Nation's First Amounts of HALEU
[10] In some cases, deconversion into UF_4 may be requested. UF_4 is considered more chemically stable than UF_6 and may be preferred for long-term storage or as an intermediate product before further processing into metallic uranium: WNA | Uranium Conversion

1.2 HALEU Supply Production Challenges and Demand Uncertainty

The main factor limiting private investment in new domestic HALEU production capacity is the significant uncertainty in long-term market demand for HALEU that depends heavily on timing and volume of advanced reactor deployment in the late 2020s and beyond. Lack of demand certainty limits investment in guaranteed supply (new HALEU production capacity) and lack of supply certainty limits investment in guaranteed demand (new advanced reactors that will use HALEU).

Establishing a high-confidence and robust HALEU market demand projection requires accurate identification of the demand from future commercial deployment of advanced nuclear reactors. Understanding the anticipated fuel requirements of these advanced reactor technologies would enable both DOE and commercial HALEU producers to effectively plan for and deploy the required HALEU infrastructure to meet future demand, ensuring a steady and reliable supply of HALEU for the successful deployment and operation of advanced nuclear reactors. These market projections, however, are necessary but may not be sufficient to catalyze industry investment in new HALEU production capacity. Guaranteed or "firm" contracts for HALEU off-take may also be needed by companies to justify new capital investments on their balance sheets or to secure debt financing for major projects.

Near-term demand will be based on advanced reactor fuel testing and development activities,[11] FOAK commercial and test reactors including the Advanced Reactor Demonstration Program (ARDP) Pathway 1 awardees,[12] and potentially FOAK microreactors for Department of Defense advanced nuclear energy projects.[13] Cumulative HALEU demand for these near-term activities could exceed 40 MTU of HALEU by the end of the decade.[14]

The near-term supply of HALEU is constrained to a small number of private and government sources. The only commercial source of HALEU prior to 2022 (Russian company TENEX) was considered suitable for initial advanced reactor cores, but they were not considered a reliable commercial partner for long-term operations. Following the 2022 Russian invasion of Ukraine, advanced reactor developers, advance reactor developers, prospective customers, and government leaders concluded that relying on TENEX for any HALEU is an unacceptable commercial and political risk.

Multiple Western companies (including Centrus, Urenco, Orano, and Global Laser Enrichment) have expressed commercial interest in developing HALEU production capabilities in the near term, but the companies have made varying levels of commitment and investments.

The U.S.-based company Centrus has been working to develop domestic HALEU production capacity since 2019 and received a $30 million DOE award in November 2022 to operate the HALEU enrichment facility in Piketon, Ohio with plans to produce 0.6 MTU/year of HALEU.[15] Operation of the Centrus HALEU

[11] DOE | HALEU Availability Program

[12] The ARDP Pathway 1 awardees are the two projects selected by DOE for a public-private cost-share deployment of their advanced reactor design. The awardees were the TerraPower *Natrium* reactor project and the X-energy *Xe-100* reactor project. Both projects will require HALEU fuel for both their initial core load and core reloads.

[13] PNNL| Military Mobile Nuclear Power

[14] Reuters | U.S. Ramps Up Advanced Fuel Production Capabilities

[15] DOE | DOE Announces Cost-Shared Award for First-Ever Domestic Production of HALEU for Advanced Nuclear Reactors

enrichment facility was designed as an initial demonstration of Centrus' HALEU production capabilities. DOE has contract options to continue HALEU production at Centrus at 0.6 MTU/year through 2032.[16] Centrus has also publicly stated that the facility output could be expanded by 6 MTU per year within 42 months with "sufficient additional funding or off-take contracts" for HALEU production and could further increase production by an additional 6 MTU per year every six months afterward given adequate business conditions.[17] Any new production capacity, however, is dependent on securing guaranteed or "firm" contracts from HALEU customers.

The British-German-Dutch based company Urenco has been working to expand its U.S. enrichment capacity and position itself for future expansion into HALEU production. The Urenco USA uranium enrichment facility in Eunice, New Mexico currently has a capacity of 4,600 kSWU per year and Urenco announced plans in July 2023 to expand the plant capacity by another 700 kSWU per year.[18] Urenco USA has announced plans to enable the production of enriched uranium up to 10% U-235 at the Eunice facility[19] and is working with the NRC to amend its existing license to enrich uranium up to 10% U-235.[20] Finally, Urenco has not announced formal plans to establish HALEU production capacity in the U.S. but has stated that it will pursue the design, licensing, construction, and operation of new HALEU production facilities subject to firm customer commitments.[21]

The French-based company Orano and the U.S.-based company Global Laser Enrichment (GLE) have both expressed interest in developing HALEU production capabilities but do not currently have commercial enrichment facilities in the United States. Orano has stated that it is interested in leveraging its existing uranium production infrastructure to meeting HALEU demands.[22] Lack of firm demand signals was cited by Orano as a key barrier to commercial investment in new HALEU production capacity.[23] GLE has stated that its technology (laser enrichment technology as opposed to traditional gas centrifuge technology) is "well suited to producing HALEU"[24] and that there are opportunities for GLE to produce HALEU given sufficient market signals.[25] These two companies have not yet announced plans to invest in new HALEU production facilities, but Orano's established uranium supply chain and GLE's next-generation enrichment technology position them to play a role in deploying near-term HALEU production capacity.

Additional stop-gap pathways for HALEU production have been proposed that do not require new HALEU enrichment infrastructure. These pathways include the recovery of HALEU from prior DOE fuel programs and downblending of excess high-enriched uranium (HEU) from DOE stockpiles that could be used to help meet commercial HALEU demand. These alternative HALEU production pathways have unique challenges due to the availability of material, availability of qualified facilities and personnel, and the time and funding required to make material available. Appendix A provides additional details on the challenges associated with these alternative HALEU production pathways. Ultimately, these alternative pathways are stop-gaps and new HALEU production capacity is required to meet long-term advanced reactor needs.

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[16] Centrus Energy Corp | Centrus Energy Finalizes Contract with U.S. DOE to Complete HALEU Cascade Construction
[17] Centrus Energy Corp | Centrus Makes First HALEU Delivery to U.S. Department of Energy
[18] Urenco USA | Urenco's First Capacity Expansion to be at its US Site
[19] Urenco | 2021 Next Generation Fuels
[20] Urenco USA | Notice of Intent to submit License Amendment Requests for changes Enrichment Limit
[21] Urenco USA | 2022 HALEU RFI Response
[22] TradeTech | Spotlight on Technology - Orano USA's HALEU Program
[23] Orano USA | 2022 HALEU RFI Response
[24] GLE | Inflation Reduction Act Press Release
[25] GLE | Technology Commercialization Update

Long-term demand for HALEU will be dictated by the initial core loads of other FOAK commercial and test reactors, including those associated with the ARDP's Risk Reduction and Advanced Reactor Concepts (ARC-20) awardees.[26] The core reloads of near-term deployed reactors and the initial cores for subsequent reactors, spanning all the way to nth-of-a-kind (NOAK) reactors, will significantly shape long-term demand. Additional HALEU demand may result from the National Nuclear Security Administration's (NNSA's) research reactor fuel availability program, future expansion of the Department of Defense (DoD) microreactor program, and potential use of advanced reactors to support National Aeronautics and Space Administration (NASA)[27] or DoD space missions.[28]

Estimates of HALEU requirements will consequently vary depending on the deployment rate of advanced reactor technologies across commercial as well as civilian, defense, and other federal customers. Recent projections from Idaho National Lab (INL) suggest a cumulative production of 5,350 MTU of HALEU will be needed by 2050 to support deep decarbonization goals, with a production rate of approximately 520 MTU/year required by 2050.[29] To meet this substantial demand, the United States must swiftly ramp up its HALEU production capacity (with corresponding increases in uranium production) to ensure that future reactors have an ample supply of fuel to generate clean energy.

1.3 Current Status of the HALEU Availability Program

The United States is already taking steps to accelerate the development of a robust domestic HALEU supply chain. The Energy Act of 2020 authorized the U.S. Department of Energy (DOE) to establish a program to support the availability of HALEU for civilian domestic research, development, demonstration, and commercial use. This authorization, along with the additional funding provided in the Inflation Reduction Act (IRA), emphasizes the important role DOE will play in facilitating the supply of fuel for advanced nuclear reactors. DOE is currently in the initial stages of implementing this program, known as the U.S. HALEU Availability Program (HAP), which aims to support a nascent domestic HALEU supply chain, enabling the United States to meet the fuel demands of advanced nuclear technologies and solidify its position as a leading provider in the global market.

A major role of the HAP is to catalyze private investment in HALEU commercial production facilities. The HAP can create a strong market signal for new investment in HALEU production by providing both an initial demand signal for HALEU enrichment and providing supply-side financial support for HALEU production. Creation of HALEU market provides a more stable framework for demand due to private advanced reactor participation, as it offers a high confidence line-of-sight to fuel availability for subsequent advanced reactor deployments. Increased fuel demand signals from the private sector, combined with government investment in HALEU infrastructure, can lead to the development of a robust HALEU supply chain and a fully developed and self-sustaining private HALEU market. If properly funded and implemented

[26] The ARDP Risk Reduction and ARC-20 awardees were additional project selected by DOE for support by ARDP for activities other than a full reactor demonstration. The Risk Reduction awardees included Kairos Power Hermes reactor, Westinghouse eVinci microreactor, BWXT advanced nuclear reactor, Holtec SMR-160, and Southern Company Molten Chloride Reactor Experiment. The ARC-20 awardees included ARC Clean Technology ARC-100, General Atomics Fast Modular Reactor, and Boston Atomics Horizontal Gas Reactor. Seven of the eight ARDP Risk Reduction and ARC-20 awardees technologies will require HALEU fuel.

[27] NASA | Space Nuclear Power and Propulsion (SNPP) Program

[28] DOD DARPA | Demonstration Rocket for Agile Cislunar Operations (DRACO)

[29] INL | Estimated HALEU Requirements for Advanced Reactors to Support a Net Zero Emissions Economy by 2050

effectively, the HAP can eliminate the "chicken and the egg" dilemma that exists between the supply-side and demand-side needs of an emerging HALEU market.

The transition from a government-supported market to a commercial market is critical because government financial support for HALEU production cannot be sustained indefinitely. Specifically, any federal funding for the HAP is currently set to expire in 2032. This limited timeframe is the key catalyst for private investment, as companies recognize the temporary nature of government funding and the subsequent need for sustainable market solutions. The expectation is that by the end of the government funding period, a commercial HALEU market will be fully formed, driven by private sector participation and investment, ensuring the long-term viability and success of the domestic HALEU industry.

The DOE has also created a HALEU consortium to support the implementation of the HAP.[30] The consortium is made up of advanced reactor developers, industry-aligned trade groups, and potential HALEU users and industrial partners, with an overall goal to inform HAP activities carried out by DOE. In June 2023, the Office of Nuclear Energy (NE) released a Notice of Intent (NOI) inviting public comment on the scope of an upcoming draft environmental impact statement (EIS) that will analyze the environmental impacts of DOE's proposed action to facilitate the commercialization of domestic HALEU production.[31] NE also issued a final deconversion requests for proposal (RFP),[32] and plan to issue a final enrichment RFP, to acquire HALEU, thereby soliciting a public-private partnership to put in place the contracts needed to start building HALEU supply chain infrastructure in the U.S.[33]

The HAP has been funded to date using a single large appropriation from Congress. The Inflation Reduction Act (IRA) of 2022 included $700 million for the HAP. Of that $700 million, $500 million is allocated to the production of HALEU. Of the $200 million remaining, $100 million is designated to go towards designing and licensing HALEU transportation systems, and the rest ($100 million) will support other activities that assure the availability of HALEU for research, development, demonstration, and commercial use. This funding is also time sensitive – the HAP funding provided by IRA must be spent by September 30, 2026.[34] A successful HAP that meets the overall goal of catalyzing private investment in HALEU production, however, will require significantly more appropriations than the $500 million thus far directly appropriated.

DOE and Congress's actions demonstrate a clear commitment to the HAP and to ensuring a robust supply of HALEU for advanced nuclear reactors in the United States. While these initial actions are a positive step forward, it is important to recognize that many challenges still face effective execution of the program.

1.4 Addressing Challenges of Catalyzing Private Investment in HALEU Production

Despite stakeholder agreement that a domestic commercial HALEU market and fuel cycle is needed, and recent DOE action, there has been limited discussion of the market characteristics needed to provide adequate assurance of fuel availability. The Nuclear Innovation Alliance (NIA) published a report titled

[30] DOE | HALEU Consortium
[31] DOE | Notice of Intent to Prepare an EIS for HAP Activities in Support of Commercial Production of HALEU
[32] DOE | U.S. Department of Energy Issues HALEU Deconversion Request for Proposals
[33] DOE | U.S. Department of Energy to Acquire HALEU Material
[34] DOE | HALEU Availability Program

"Catalyzing a Domestic Commercial Market for HALEU" [35] in April 2022 that addressed questions related to implementation of a HALEU availability program. The report described the challenges and opportunities associated with development of a domestic commercial HALEU market and identified potential policy options that can be used to catalyze market development. It also presented the changing near-term, mid-term, and long-term supply and demand conditions that must be considered when developing federal programs to accelerate commercial market development.

Subsequent discussions with industry stakeholders and policymakers have highlighted additional questions related to the economics of HALEU production and the supply and demand conditions needed for the successful implementation of the HAP. This new report seeks to address these questions by characterizing the cost drivers for HALEU production, examining the costs throughout each phase of HALEU production cycle, and developing a model to quantify HALEU production costs and identify cost drivers that will most significantly impact HALEU costs. Characterizing each major step of the HALEU production process (mining, milling, conversion, LEU enrichment, HALEU enrichment, and HALEU deconversion) enables the development of a HALEU production cost model. Insights from a HALEU production cost model (including understanding of major cost drivers and uncertainties) enables more robust discussion, advocacy, and informed decisions regarding the most efficient and cost-effective implementation and funding of the HAP.

The HALEU production cost model is used as the basis for two analyses that provide more detailed insights on how the HAP can catalyze investment in commercial domestic HALEU production. The analysis helps outline the programmatic and appropriation requirements of different implementations of the HAP. The first new analysis is a detailed evaluation of the current programmatic implementation of the HAP: a HALEU "off-take" program in which the federal government makes guaranteed off-take or purchase contracts for HALEU to create a reliable demand signal for commercial investment. The second new analysis is a proposal and detailed evaluation of a modified programmatic implementation of the HAP: a HALEU "enrichment service agreement" program in which the federal government makes guaranteed contracts for HALEU enrichment as a service to create a reliable demand signal for commercial investment.

The characterization of cost drivers, development of a HALEU production cost model, and quantitative analysis of policy options are intended to increase policymaker and stakeholder understanding of HALEU costs and markets and provide a transparent and repeatable framework for quantitative policy analysis. This paper can help inform policymaker and stakeholder discussions, advocacy, and decision making on the programmatic implementation and appropriation support needs for the HAP, enabling the effective and efficient catalyzation of a robust, sustainable, competitive, domestic commercial HALEU market.

[35] NIA | Catalyzing a Domestic Commercial Market for HALEU

2 HALEU Production Cost Model

Development of a HALEU production cost model enables a more accurate evaluation of HALEU production costs based on known costs for HALEU production, identification of cost uncertainties for HALEU production, and the prioritization of future work on new cost estimations that will have the most significant impacts on the HALEU production cost or cost uncertainty. This chapter provides a conceptual model for stages of HALEU production, quantifies the enrichment required to produce HALEU, develops a quantitative cost model for HALEU production costs, and quantifies the costs of HALEU production under a variety of different market assumptions. The HALEU production cost model presented in this chapter can be used by stakeholders and policymakers to assess the costs of HALEU under different assumptions and compare expected HALEU production costs using a consistent conceptual model.

The following subsections provide the technical basis for a HALEU production cost model, including:

- Quantifying HALEU production process (Section 2.1)
- Quantifying HALEU production costs (Section 2.2)
- Results of the HALEU production cost model (Section 2.3)
- Summary and discussion of HALEU production costs (Section 2.4)

It is important to note that Sections 2.1 and 2.2 provide the derivation of the technical analysis and quantification of a HALEU production cost model while Sections 2.3 and 2.4 provide the results of the cost model and implications for catalyzing commercial HALEU production.

2.1 Quantifying HALEU Enrichment Processes

Quantifying the HALEU enrichment process requires characterization of the different physical processes and quantification of the relationships between relevant physical parameters. This section provides the technical derivation of the HALEU enrichment process in terms of the process mass flows, process enrichment levels, and separative work[36] required to enrich uranium. It also provides a quantitative and qualitative evaluation of different strategies for HALEU enrichment including production of HALEU from natural uranium feedstock or production of HALEU from LEU feedstock. These derivations and quantitative evaluations are the basis for both the HALEU production cost model and assessment of different HALEU production programs. An understanding of these derivations provides valuable insights into the difference between different HALEU enrichment strategies and costs, but are not required to understand the final HALEU production cost model or program analyses.

The following subsections provide the derivations and quantitative evaluations for a HALEU enrichment process:

- Deriving the mass flows, enrichments, and separative work for uranium enrichment (Section 2.1.1)
- Evaluating 1-step versus 2-step HALEU enrichment processes (Section 2.1.2)

This section provides quantitative evaluations of mass flows, enrichments, and separative work for uranium enrichment under different process input and output conditions that are used in Section 2.2 as the basis for the HALEU production cost model. Additional details on the quantitative derivations of mass

[36] See section 2.1.1 for a description of "separation work"

flows, enrichments, and separative work for uranium enrichment under different process input and output conditions are provided in Appendix B.

2.1.1 Deriving Mass Flows and Separative Work for Uranium Enrichment

The uranium enrichment process is characterized by the material input and outputs of the enrichment process and the amount of enrichment "work" required to separate the input and output streams.

The input for the enrichment process is termed the process "feed" and is characterized by the quantity of material and the enrichment level of the material. The output for the enrichment process is separated into two streams: the process "product" and the process "tails". The "product" is the desired output stream of the enrichment process (with a higher enrichment of U-235 compared with the feed) and the "tails" are the remaining output of the enrichment process (with a lower enrichment of U-235 compared with the feed). Both the product and the tails are characterized by the quantity of material and the enrichment level of the material.

The amount of enrichment "work" necessary to separate the process product and tails from the process feed is termed the separative work required for enrichment. The amount of enrichment "work" is characterized by the separative work unit (SWU). The SWU is a dimensionless number that is calculated based on the mass flows and enrichment of uranium input and output streams.

The material input and outputs of the enrichment process and the amount of separative work for uranium enrichment are described by:

$$W_{SWU} = P \cdot V(x_P) + T \cdot V(x_T) - F \cdot V(x_F) \quad \text{[Equation 1]}$$

where:

- W_{SWU} is the amount of "separative work" required by the enrichment process to separate the process inputs (F) into the process outputs (P, T) with specific enrichment levels measured in separative work units (SWU)
- P is the mass of "product" output from the enrichment process measured in kilograms
- $V(x_i)$ is a mathematic value function that describes symmetric logarithmic system behavior based on input x_i, where $x_i = x_P, x_T, \text{or } x_F$. The value function is explicitly described below in Equation 2 and plotted in Figure 3.
- x_P is the enrichment of the "product" from the enrichment process (%U-235 enrichment)
- T is the mass of "tailings" output from the enrichment process measured in kilograms
- x_T is the enrichment of the "tailings" from the enrichment process (%U-235 enrichment)
- F is the mass of "feed" input to the enrichment process measured in kilograms
- x_F is the enrichment of the "feed" into the enrichment process (%U-235 enrichment)

The value function $V(x_i)$ in Equation 1 is described by:

$$V(x_i) = (2x_i - 1) \cdot \ln\left(\frac{x_i}{1-x_i}\right) \quad \text{[Equation 2]}$$

The value function $V(x_i)$ in Equation 2 is also plotted in Figure 3:

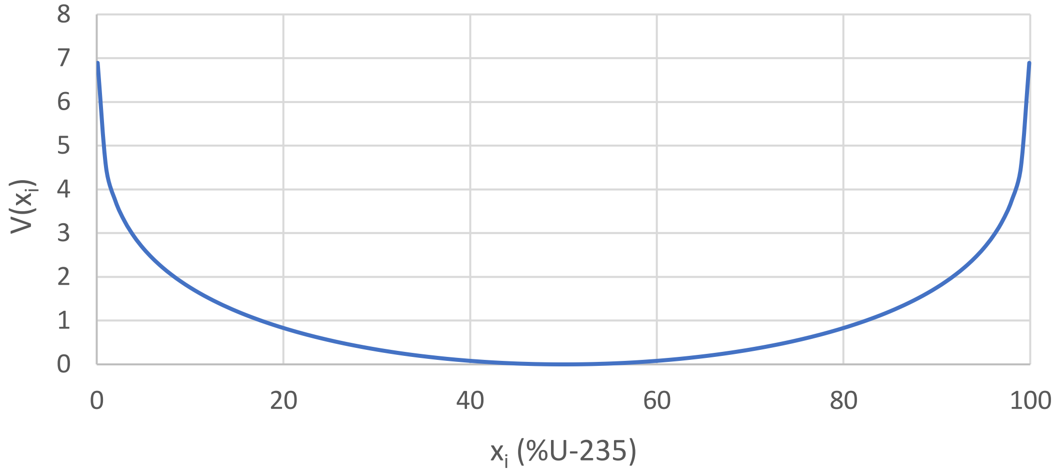

Figure 3. Value Function $V(x_i)$ for Different Uranium Enrichments (%U-235).

The conceptual relationship between each of the physical variables related to uranium enrichment (Equation 1) are visualized in Figure 4.

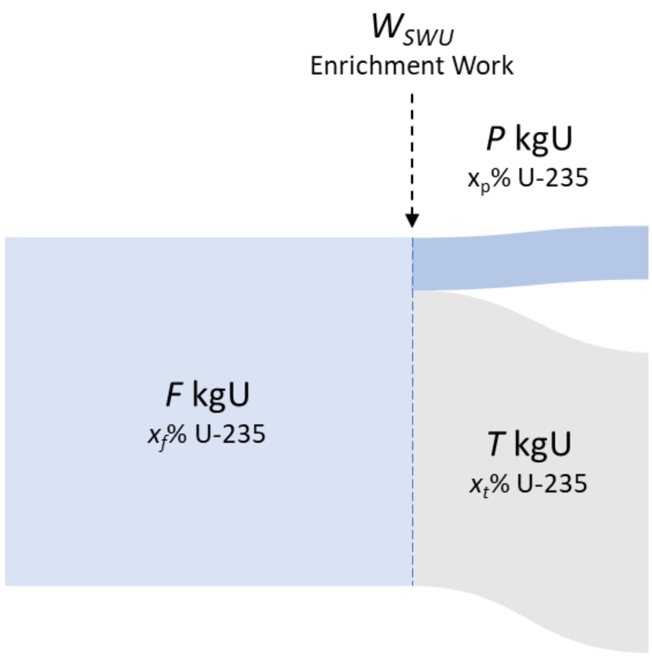

Figure 4. Uranium Enrichment Variables.

One specific useful case to solve is to determine the quantity of SWUs (W_{SWU}), the amount of uranium feed input (F), and the uranium tails output (T) based on a defined amount of uranium production output (P), and the enrichment of all input and output streams (x_P, x_T, x_F).

For this specific case, the three simultaneous equations to solve then reduce to the following equations:

$$F = P\left(\frac{x_P - x_T}{x_F - x_T}\right) \quad \text{[Equation 3]}$$

$$T = P\left(\frac{x_P - x_F}{x_F - x_T}\right) \quad \text{[Equation 4]}$$

$$W_{SWU} = P\left[(2x_P - 1)\cdot\ln\left(\frac{x_P}{1-x_P}\right) + (2x_T - 1)\left(\frac{x_P - x_F}{x_F - x_T}\right)\ \ln\left(\frac{x_T}{1-x_T}\right) - (2x_F - 1)\left(\frac{x_P - x_T}{x_F - x_T}\right)\ln\left(\frac{x_F}{1-x_F}\right)\right] \quad \text{[Equation 5]}$$

These equations are the basis for evaluating the mass flows (kg) and separative work (SWU) with different production outputs (kg) and enrichments (% U-235). The mass flows and separative work can then be used to quantify the costs associated with uranium feed inputs $\left(C_{input}\right)$, uranium conversion costs $\left(C_{convert}\right)$, and enrichment costs $\left(C_{enrich}\right)$. These derived equations relating enrichment process inputs, outputs, and work are the basis for the calculations performed in the following sections.

A complete derivation of these equations is provided in Appendix B.

2.1.2 Evaluating Dedicated Versus Separated HALEU Enrichment Processes

Uranium enrichment and isotope separation are logarithmic processes where small increases in the feed enrichment (x_F) at low enrichments can significantly reduce the required amount of uranium feed (F) and separative work (W_{SWU}) required to produce a fixed quantity of material (P) at a higher target enrichment (x_P). As the feed enrichment approaches the target enrichment (i.e., as x_F approaches x_P), these reductions are less significant. Figure 5 plots the amount of separative work and uranium feed required to produce one kilogram of HALEU enriched to 19.75% for different uranium feed enrichments using Equations 3 and 5 derived above.

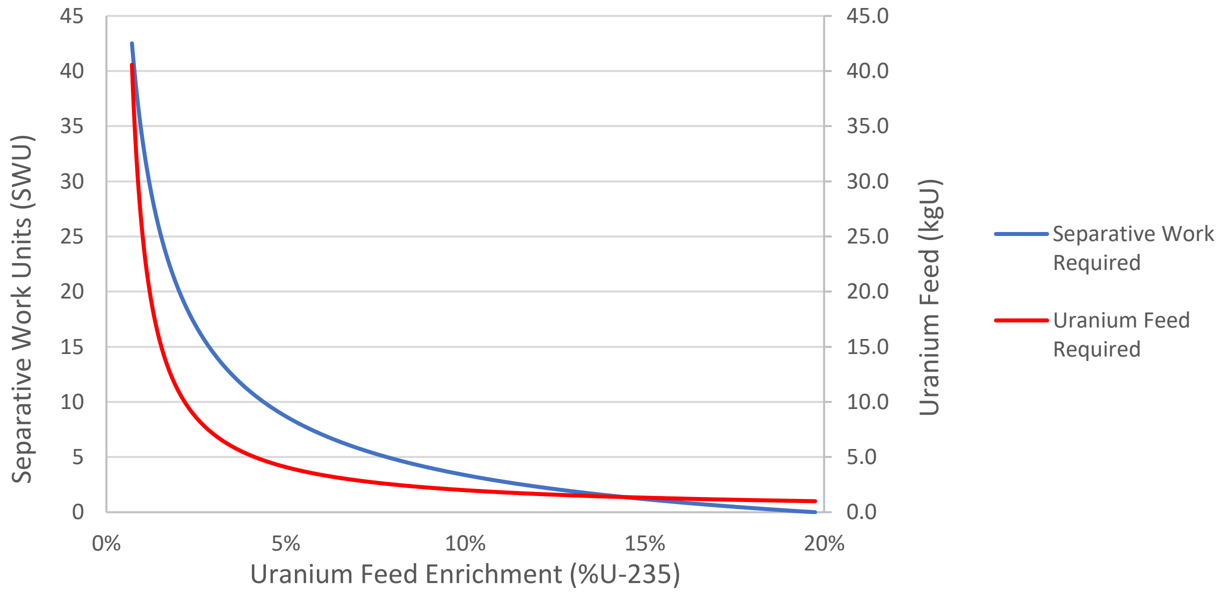

Figure 5. Uranium Feed (F) and Separative Work (W_{SWU}) Requirements to Produce 1 kg of 19.75% HALEU as a Function of Uranium Feed Enrichment (x_F).[37]

[37] The calculation to produce this figure assume a constant process tails enrichment (x_T) of 0.23% U-235.

Figure 5 illustrates that starting with higher enrichment uranium feed material can significantly reduce the additional enrichment required to produce HALEU. This enrichment must still be completed to produce the feed material (e.g., enriching natural uranium at 0.711% U-235 enrichment to LEU at 4.95% U-235 as feed material for HALEU), but dividing the HALEU enrichment process into multiple process steps based on the enrichment level can enable the more efficient allocation of separative work across different enrichment facilities designed and optimized for processing uranium with differing enrichment levels.

This section quantifies and compares the mass flows and separative work for two enrichment processes:

- 1-step HALEU enrichment process where natural uranium (0.711% U-235) is enriched to HALEU (19.75% U-235) in a single enrichment facility that is dedicated to HALEU production
- 2-step HALEU enrichment process where natural uranium (0.711% U-235) is enriched in the first step of the process to LEU (up to 4.95% U-235) and then further enriched in the second step of the process to HALEU (19.75% U-235)

These two enrichment processes are selected for analysis because of the existing commercial LEU supply chain for uranium enriched up to 4.95% U-235. The existing LEU supply chain could enable enrichment companies to purchase uranium feed at higher enrichments (e.g., 4.95% U-235) as a commodity and maximize material production (kgU) from a HALEU enrichment facility given a fixed facility enrichment capacity (SWU/y). These two enrichment processes represent the most likely near-term pathways for production of HALEU and are used as the starting point for quantitative analysis.[38]

Quantifying the mass flows and separative work for different steps of the HALEU enrichment processes enables a better characterization of cost scenarios that may utilize different LEU and HALEU enrichment facilities (with differing SWU costs) or scenarios where LEU feed is purchased from other commercial suppliers as a commodity product. For example, for a 2-step HALEU enrichment process, LEU could be purchased from a supplier on the open LEU commodity market and used as feed in a HALEU enrichment

[38] There are additional multi-step HALEU enrichment processes that are possible based on staging the enrichment of HALEU across multiple enrichment operations. A 3-step HALEU enrichment process is technically feasible where LEU feed material (e.g., enriched to 4.95% U-235) is further enriched in an intermediate enrichment facility up to 10% U-235 (typically described as LEU+) before enrichment to the final concentration in a HALEU enrichment facility. This 3-step HALEU enrichment process further reduces the amount of enrichment work required in a dedicated HALEU enrichment facility and could leverage lower separative work costs in lower enrichment (e.g., LEU+) facilities.

One challenge of the 3-step HALEU enrichment process is that production facilities for LEU+ enrichment materials are limited. While there is commercial interest in production of LEU+ for existing reactors (specifically to support development of high-burn up and accident tolerant fuels), LEU+ is not currently available commercially as a commodity product. It is not clear that, in the near term, use of separate LEU+ enrichment facilities or use of LEU+ as feed for HALEU production is commercially feasible or attractive. If future HALEU demand is limited by available HALEU enrichment capacity (i.e., SWU/year) but excess LEU+ enrichment capacity is available, use of separate LEU+ enrichment facilities or use of LEU+ as feed for HALEU production could be used to increase HALEU production (i.e., MTU/year) by a factor of 6-7 based on the ratio of separative work required for enrichment from 4.95% U-235 to 9.75% U-235 (5.02 SWU with 0.711 % U-235 tails) to the separative work required for enrichment from 9.75% U-235 to 19.75% U-235 (0.87 SWU with 4.95 % U-235 tails).

The use of separate LEU+ enrichment facilities or use of LEU+ as feed for HALEU production is not evaluated further in this report for the HALEU production cost model analysis or HALEU program evaluations.

facility. Alternatively, a company with existing LEU enrichment facilities could use these facilities to produce LEU feed for a HALEU enrichment facility.

Table 1 summarizes and compares the 1-step and 2-step HALEU enrichment processes. The separative work (SWU) and the mass flows required to produce 1 kg of 19.75% U-235 enriched uranium are presented for both HALEU enrichment process. Figure 6 illustrates the mass flows and separative work of a dedicated (1-step) HALEU enrichment process. Figure 7 illustrates the mass flows and separative work of a separated (2-step) HALEU enrichment process.

Table 1. HALEU Enrichment from LEU Feed Calculations

		1-Step HALEU Enrichment Process	2-Step HALEU Enrichment Process	
	Cases:	HALEU from Natural Uranium Feed (0.711% U-235)	LEU Feed from Natural Uranium Feed (0.711% U-235)	HALEU from LEU Feed (4.95% U-235)
Knowns				
P	kg	1	4.5	1
x_P	% U-235	19.75	4.95	19.75
x_T	% U-235	0.23	0.23	0.711
x_F	% U-235	0.711	0.711	4.95
Unknowns				
W_{SWU}	SWU	42.52	36.63	5.89
F	kg	40.6	40.6[39]	4.5
T	kg	39.6	39.6	3.5

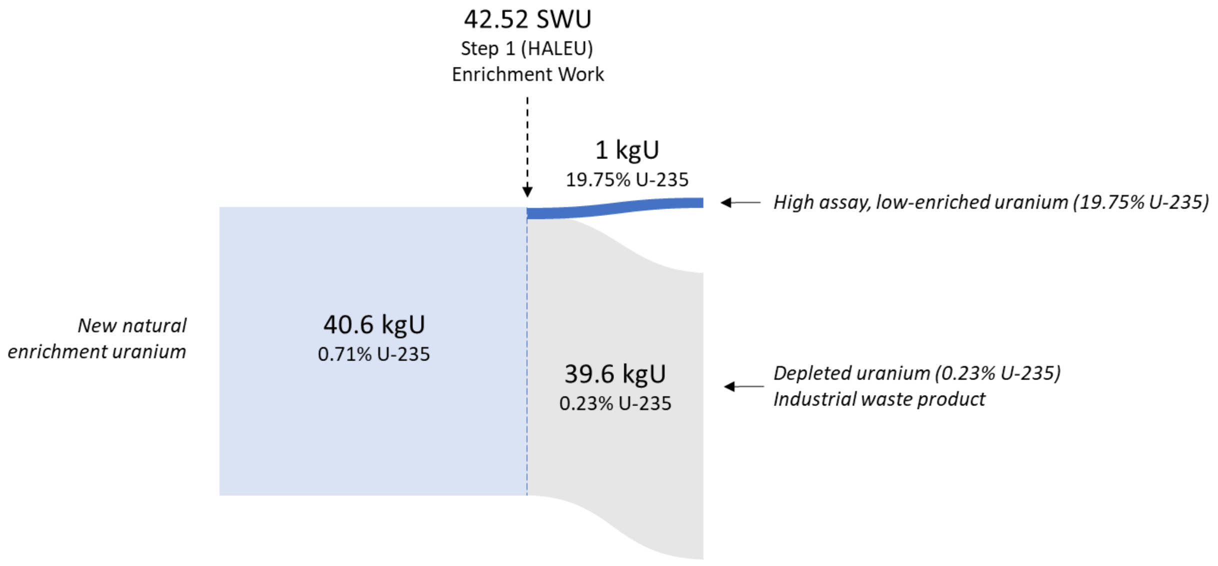

Figure 6. 1-Step HALEU Enrichment Process Flow Diagram

[39] This feed in based on new natural uranium. The enrichment process would also use 3.5 kg of 0.71% enriched U-235 tails from the HALEU enrichment process as additional feed material for a total enrichment feed of 44.1 kg.

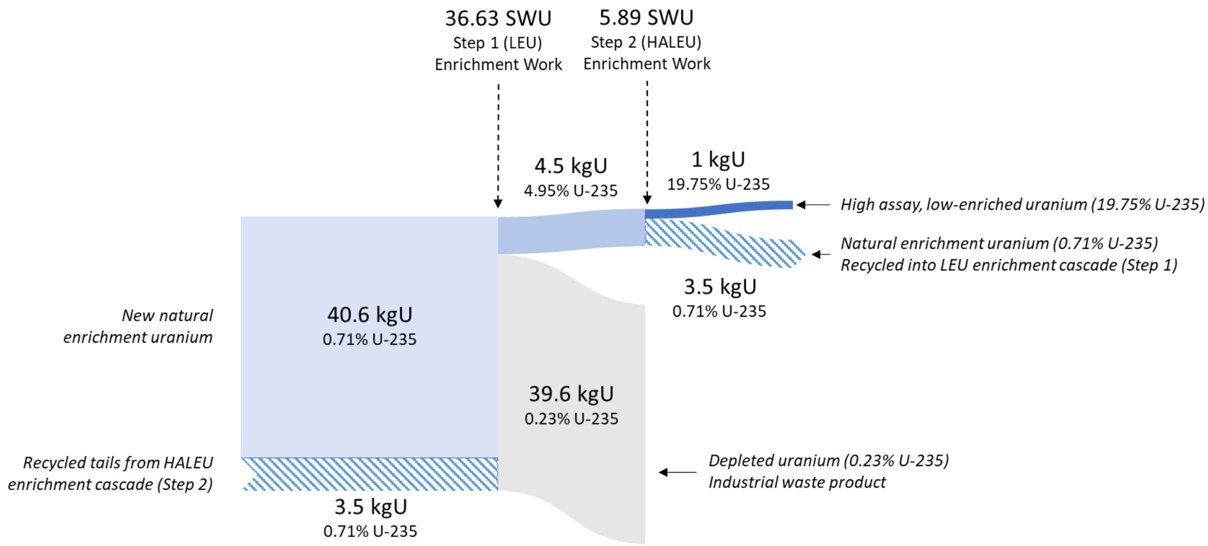

Figure 7. Separated (2-Step) HALEU Enrichment Process Flow Diagram

Independently analyzing these two different process cases enables a better characterization of cost scenarios that may utilize multiple LEU and HALEU enrichment facilities (e.g., facilities with differing SWU costs, separation capacities, or production capacities[40]) or scenarios where LEU is purchased from other commercial suppliers as a commodity product. The calculations in Table 1 show that both the 1-step and 2-step enrichment processes require the same total enrichment (i.e., 42.52 SWU in the 1-step process for HALEU enrichment equals the sum of 36.63 SWU and 5.89 SWU in the 2-step process for LEU and HALEU enrichment, respectively) and natural uranium mass (i.e., each process requires an initial feed of 40.6 kg of natural enrichment uranium), but that there is a significant difference in the distribution of enrichment activity between the processes.

The dividing LEU and HALEU enrichment activities into multiple steps may be important if there is excess LEU enrichment capacity or low market cost for LEU, but limited HALEU enrichment capacity. A HALEU production facility with a fixed total separative capacity (SWU/y) can, in principle, produce 7.2 times more HALEU by mass by using a 2-step enrichment process (using 4.95% U-235 feed) as compared with using a 1-step enrichment process (using natural uranium feed) due to the significantly lower separative work required for LEU feed (5.89 SWU) compared with natural uranium feed (42.52 SWU).

Further optimizing a 2-step HALEU enrichment process (e.g., changing feed enrichment, tails enrichment, or mass flows) could maximize HALEU production (e.g., MTU/y) for a fixed HALEU facility separation capacity (e.g., SWU/y). For example, if LEU was readily available on international markets, a HALEU enrichment facility could operate with a higher tail enrichment (e.g., above the 0.711% U-235 assumed in Table 1). Using the equations in Section 2.1.1, it can be shown that higher tail enrichment would enable HALEU production using a greater amount of enriched feed material (e.g., LEU at 4.95% U-235) but a lower amount of separative work (e.g., less than 5.89 SWU per kg HALEU).

The actual design and operation of the HALEU enrichment facility would depend significantly on enrichment and feed material costs, process design and operation considerations, as well as the market demand for both LEU and HALEU.

[40] Factors that may drive differences in SWU cost between LEU and HALEU facilities are discussed in Section 2.2.2.

2.2 Quantifying HALEU Production Costs

This section proposes a HALEU production cost model and quantifies the major cost drivers at each stage of the HALEU production process. A detailed HALEU production cost model provides the technical basis for the HALEU production cost analysis (Section 2.3) and policy and programmatic implications of HALEU production costs (Section 2.4). The cost model and cost drivers presented in this section provide important insights into the difference between different HALEU enrichment processes (e.g., 1-step or 2-step model discussed in Section 2.1.2) and the relative importance of different HALEU production costs components.

Detailed understanding of the production cost model and cost drivers presented in this section is not required to understand the final production costs (Section 2.3 and 2.4) or evaluation of different HALEU production programs (Section 4).

The following subsections provide the technical basis for a HALEU production cost model and discussion of key cost drivers including:

- HALEU production cost model (Section 2.2.1)
- Quantifying HALEU enrichment costs (Section 2.2.2)
- Quantifying HALEU deconversion costs (Section 2.2.3)

This section provides conceptual and quantitative evaluations of HALEU production costs under different conditions that are used in Section 2.3 to support HALEU production cost analyses. Detailed quantification of HALEU enrichment and deconversion costs are provided in this section due to the need for new fuel cycle infrastructure and facilities (specifically HALEU enrichment capacity and HALEU deconversion capacity) to support production.

Detailed discussion of all HALEU production cost drivers (including mining, conversion, enrichment, deconversion, and production overhead) is provided in Appendix C.

2.2.1 HALEU Production Cost Model

Production of HALEU fuels for advanced reactors requires both design-specific and design-independent processes and facilities. The production of HALEU fuels can be separated into three major processes with increasing levels of design specificity:

- Production of converted NU or LEU feed: applicable to all LEU- or HALEU-fueled reactors and requires processes and facilities that are already commercially mature
- Production of enriched and deconverted HALEU: applicable to all HALEU-fueled reactors and requires new processes and facilities for HALEU enrichment and deconversion into solid oxide or metallic forms
- Production of HALEU fuels: applicable to individual designs and technologies, and characterization requires detailed knowledge of a specific fuel form and application.

The HALEU Availability Program was designed to catalyze private investment in the commercial facilities to produce HALEU, with the intention of making enriched and deconverted HALEU commercially available for advanced reactor fuel manufacturers and customers. HALEU fuel production will have company-specific commercial challenges and considerations, so the costs associated with HALEU fuel fabrication are not included in the generic HALEU production cost model.[41]

Figure 8 (based on the nuclear fuel supply chain description in Figure 2) illustrates the major cost drivers required to deliver HALEU as a commercial product and the costs that are included in the HALEU production cost model.

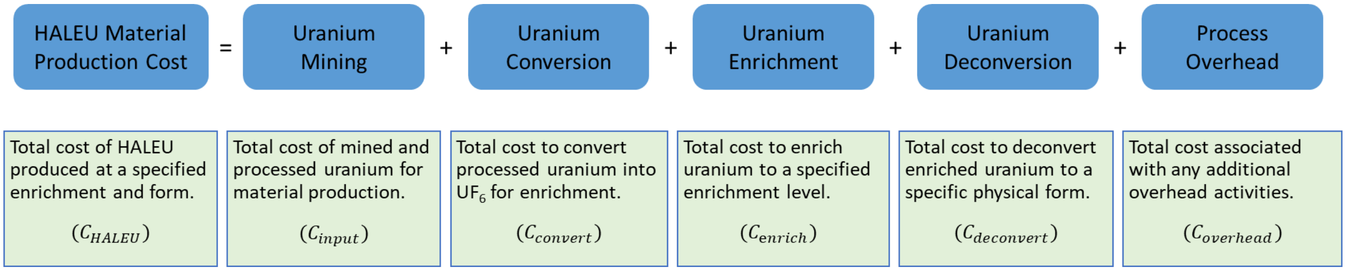

Figure 8. HALEU production cost model and cost drivers

The following sections (Sections 2.2.2 and 2.2.3) provide detailed quantification of HALEU enrichment and deconversion costs due to the need for new fuel cycle infrastructure and facilities to support these activities.

Detailed discussion of all HALEU production cost drivers (including mining, conversion, enrichment, deconversion, and production overhead) and derivation of the HALEU production cost model equations is provided in Appendix C.

2.2.2 Enrichment Costs

The enrichment cost associated with HALEU production (C_{enrich}) is a function of the quantity of separative work completed and the cost of each unit of separative work. The enrichment cost can be further characterized by enrichment cost components based on enrichment levels. Figure 9 illustrates the major cost drivers for HALEU enrichment for different enrichment levels.

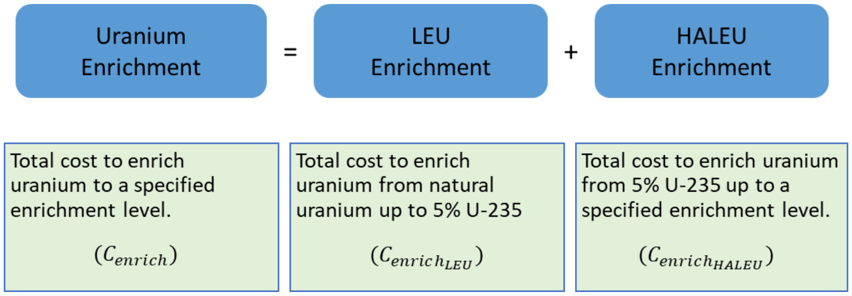

Figure 9. Uranium enrichment cost components

The enrichment costs are broken down into two components (LEU Enrichment and HALEU Enrichment) to enable more precise characterization of costs based on the different amount of separative work required

[41] The HALEU Production Cost Model presented in this section can be used to support estimation of advanced reactor fuel costs. A HALEU Fuel Cost model would need to include additional cost terms related to the specific HALEU fuel fabrication process and transportation and storage requirements for the final HALEU fuel.

for each enrichment activity and potential cost differences associated with separative work performed for differing levels of uranium enrichment. The cost associated with each category is the product of the amount of separative work required for the specific enrichment activity and the cost per unit of separative work for that activity. Figure 10 illustrates the calculation of the HALEU Enrichment cost component based on the amount of separative work required for HALEU enrichment (SWU) and the separative work cost for HALEU enrichment ($/SWU).

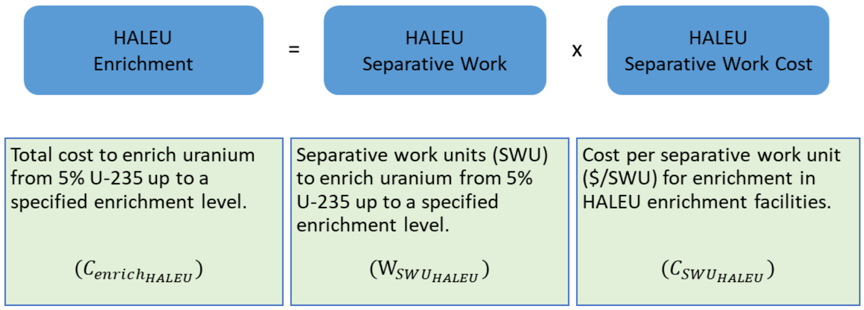

Figure 10. HALEU enrichment cost components

The generic enrichment component cost model in Figure 10 can be used to calculate enrichment component costs in Figure 9.

Evaluating the enrichment cost associated with HALEU production (C_{enrich}) requires understanding how the enrichment process will be performed. The distribution of separative work (SWU) across different enrichment cost components will depend on both the final required HALEU enrichment and whether the enrichment is completed in a one-step or two-step process (Section 2.1.2). In a 1-step HALEU enrichment process, all separative work would be completed in a HALEU enrichment facility and the price would depend on the cost of separative work performed at the facility. In the 2-step HALEU enrichment process, the separative work below 5% U-235 would be completed in a LEU enrichment facility while separative work above 5% U-235 up to the required HALEU enrichment would be completed in a HALEU enrichment facility. The generic enrichment component cost model allows the evaluation of different HALEU enrichment processes that may be used for HALEU production.

The LEU and HALEU enrichment facilities may have different separative work costs ($/SWU) based on economics of enrichment facility operation. Four major factors may contribute to cost differences between LEU and HALEU enrichment work including:

- Use of existing enrichment facilities versus construction of new enrichment facilities
- Capital payback periods associated with planned production and guaranteed contract length
- Economies of scale associated with facility production and known market size
- Regulatory and design requirements associated with producing higher enrichment uranium

HALEU enrichment is likely to have a higher separative work cost (at least initially) due to each of the above factors.

First, creating new HALEU enrichment capacity will require significant capital expenditures to support the design, licensing, construction, and commissioning of new enrichment facilities. These costs will need to be amortized across initial HALEU facility production and will increase the separative work cost for HALEU enrichment facilities compared with operating existing LEU enrichment facilities that are partially or fully amortized. This would likely increase the cost of HALEU enrichment separative work relative to LEU enrichment separative work in the near term until new HALEU facilities were amortized.

Second, the impact of amortized capital costs of new HALEU enrichment capacity on separative work costs will depend, in part, on the assumed payback period for the new facility. If a new uranium enrichment facility can amortize capital costs over a longer period of time, it will reduce the cost impact for new production. New enrichment facilities required to amortize capital costs over extremely short periods will have higher production costs than facilities with longer guaranteed contracts. The market uncertainty on long-term HALEU demands compared with LEU production may warrant a shorter payback period to ensure commercial viability for new HALEU enrichment facilities than for new LEU enrichment facilities. This would likely increase the cost of HALEU enrichment separative work relative to LEU enrichment separative work in the near term if companies are unable to guarantee long-term contracts for HALEU production.

Third, HALEU enrichment is likely to occur at small scale (on the order of 10 MTU[42] per year) due to the substantial uncertainties associated with the timing and scale of advanced reactor HALEU demand. New HALEU enrichment facilities are likely to have higher fixed capital and fixed operating costs due to both the regulatory and security requirements for nuclear facilities and modular design of uranium enrichment facilities (e.g., initial construction of a large facility footprint that can be gradually built out using modular enrichment cascades) that require higher upfront costs but enable incremental capacity expansion. These characteristics' costs will increase the separative work cost for new, smaller HALEU enrichment facilities compared with operating existing LEU enrichment facilities that can already operate at scale to meet known market demand (on the order of 400 MTU[43] per year). This would likely increase the cost of HALEU enrichment separative work relative to LEU enrichment separative work in the near term until HALEU production can be expanded to reduce the impact of fixed capital and operating costs.

Fourth, HALEU enrichment will be subject to additional regulatory and design requirements associated with producing higher enrichment uranium. In the United States, commercial quantities (i.e., greater than 10 kg) of uranium enriched above 10% U-235 but less than 19.75% U-235 is classified as special nuclear material[44] of moderate strategic significance or "Category II" material.[45] Facilities that produce Category II material are subject to elevated levels of control, physical protection, security, and material accountancy compared with existing commercial uranium facilities that produce Category III material (e.g., commercial quantities of uranium enriched to less than 10% U-235). The additional regulatory requirements and design requirements intended to prevent inadvertent critical accidents with high enrichment uranium would increase the capital costs and operating costs of a HALEU enrichment facility. This would likely increase the cost of HALEU enrichment separative work relative to LEU enrichment separative work and limit the ability to use existing LEU infrastructure to produce HALEU.

A baseline value of $1,000 / SWU is used in this analysis for the cost of one SWU performed in HALEU enrichment facilities that can enrich uranium between 5% and 19.75% ($C_{SWU_{HALEU}}$). This baseline cost estimate is subject to significant uncertainty due to limited public information and commercial experience

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[42] Production of 10 MTU HALEU per year assumed to be equal to 60,000 SWU per year based on approximately 6 SWU per kgU separative work required for enrichment of uranium from 4.95% U-235 to 19.75% U-235 in Table 1.
[43] Production of 400 MTU LEU per year assumed to be equal to 3,200,000 SWU per year based on approximately 8 SWU per kgU separative work required for enrichment of natural uranium to 4.95% U-235 in Table 1.
[44] Special nuclear materials are fissile isotopes that could be used in a nuclear reactor or nuclear weapon. Special nuclear materials include materials containing uranium-233, uranium-235, and plutonium-239.
[45] NRC | Safeguard Categories of Special Nuclear Material (SNM)

with construction and operation of new HALEU enrichment facilities. A sensitivity analysis is performed in Sections 2.3.3 and 2.3.4 to quantify the impact of varying HALEU enrichment costs on total HALEU production costs.

While a single baseline value is assumed in the analysis, the HALEU SWU cost will vary based on a wide variety of commercial factors including the facility size, fixed and variable capital costs and amortization periods, and fixed and variable operating costs. Figure 11 provides a set of example SWU cost – facility capacity curves for a hypothetical HALEU production facility to demonstrate how commercial factors may affect separative work costs for HALEU production.

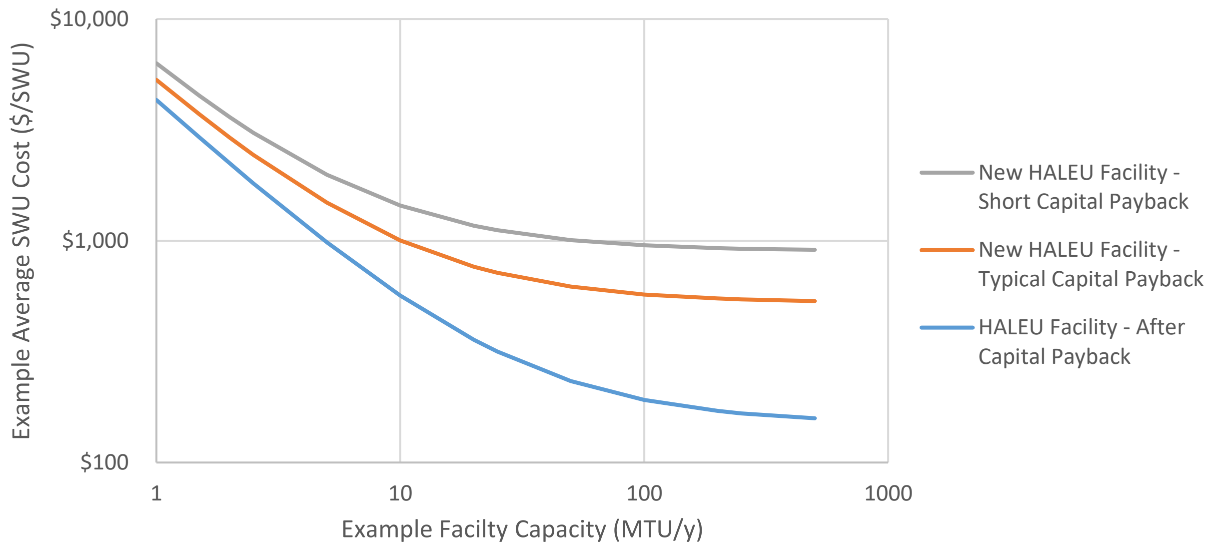

Figure 11. Example SWU cost – facility capacity curve for a hypothetical HALEU enrichment facility

The curves in Figure 11 should not be used to estimate specific HALEU SWU costs for a specific facility or set of market conditions but instead can help provide insights on the different factors that can affect HALEU SWU costs and highlight the wide range of possible costs based on specific commercial and market conditions. Additional details and discussion on factors that may affect HALEU SWU costs is provided in Appendix C.

A baseline value of $150 / SWU is used in this analysis for the cost of one unit of SWU performed in facilities that can enrich uranium up to 5% U-235 ($C_{SWU_{LEU}}$), based on typical market values for uranium enrichment in 2023.[46] A sensitivity analysis is performed in Sections 2.3.3 and 2.3.4 to quantify the impact of varying LEU enrichment costs on total HALEU production costs.

It is important to consider how new HALEU enrichment activities may affect the LEU enrichment services market. The total LEU enrichment demand associated with initial levels of HALEU production (e.g., 25 MTU per year based on the DOE draft RFP[47]) is approximately 916,000 SWU per year.[48] This total demand is small compared to overall annual total LEU enrichment used to fuel existing commercial reactors in the United States (14 million SWU in 2022) but is relatively large compared to the total capacity of the only

[46] UxC, LLC | SWU Prices

[47] DOE | U.S. Department of Energy to Acquire HALEU Material

[48] LEU enrichment demand associated with initial levels of HALEU production is based on requiring 37 SWU of LEU enrichment to produce 1 kgU of HALEU (Table 1)

commercial enrichment facility in the United States today (4.9 million SWU/yr).[49] Initial U.S. HALEU production would increase overall US LEU enrichment demand by 6.5% and may have a significant impact on market prices, especially if the LEU enrichment services required for HALEU production are only provided by domestic enrichment companies in the United States.

2.2.3 Deconversion Costs

The deconversion costs associated with HALEU production ($C_{deconvert}$) are a function of cost per kilogram to deconvert HALEU in a UF_6 form into an oxide or a metallic form. HALEU deconversion costs are challenging to estimate and likely to be much higher than existing deconversion costs due to the need for new deconversion facilities, the effects of economies of scale for small deconversion facilities, and the challenges of commercializing uranium metallization processes.

First, HALEU deconversion will require new deconversion facilities designed, licensed, and constructed to process up to 19.75% enriched uranium and processes that can deconvert UF_6 to both oxide and metallic forms. There are currently no domestic commercial operations capable of HALEU deconversion to oxide and no domestic commercial operations capable of deconversion of any enriched UF_6 to metallic form. This commercial gap will require significant infrastructure investments and commissioning of new facilities, resulting in a higher deconversion cost per kilogram compared with existing deconversion facilities and services for LEU.

Second, deconversion facilities are also extremely sensitive to economies of scale, with significant capital costs and fixed operating costs compared with variable costs. Deconversion facilities, therefore, benefit from both higher production outputs and utilization factors. Current commercial deconversion facilities collocated with LEU fuel fabrication facilities to support existing LWRs have production capacities on the order of approximately 1000 – 2000 MTU per year [50] and can perform LEU UF_6 deconversion to oxide at costs on the order of approximately \$20 – \$40 / kgU. [51] The expected capacity of demonstration facilities and initial commercial HALEU deconversion facilities will be significantly lower; facility capacity on the order of 1 – 20 MTU per year may be expected based on projected commercial HALEU demand. A significantly lower facility capacity and the high fixed costs associated with facility construction and operation (including regulatory and design costs associated with processing of higher enrichment material discussed in Section 2.2.2) will likely result in deconversion costs that are significantly higher than existing LEU deconversion costs.

Third, existing commercial experience with deconversion is limited to deconversion of UF_6 into an oxide form due to the needs of existing LWR fuel manufacturers. Commercialization of deconversion of UF_6 into a metallic form may require additional processing steps such as production of UF_4 from UF_6 through defluorination as an intermediate product before producing uranium metal using chemical reduction or converting UF_6 into an oxide form as an intermediate product before producing uranium metal using different chemical reduction processes. In both cases, deconversion of UF_6 into a metallic form may require additional deconversion processing steps (including, in some cases, deconversion to oxide) and will likely result in deconversion costs that are significantly higher than oxide deconversion costs, at least for demonstration facilities and initial commercial HALEU deconversion facilities.

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[49] WNA | Uranium Enrichment

[50] WNA | Nuclear Fuel Fabrication

[51] INL | Advanced Fuel Cycle Cost Basis – 2017 Edition (Technical Report)

A baseline value of \$2,000 / kgU is used in this analysis for $C_{deconvert}$ for oxide form deconversion and a baseline value of \$4,000 / kgU is used in this analysis for $C_{deconvert}$ for metallic form deconversion. This baseline cost estimate is subject to significant uncertainty due to limited public information and commercial experience with construction and operation of HALEU deconversion facilities, particularly for metallic deconversion processes. A sensitivity analysis is performed in Sections 2.3.3 and 2.3.4 to quantify the impact of varying HALEU deconversion costs on total HALEU production costs.

2.3 Results of the HALEU Production Cost Model

The cost analysis methodology is used to quantify the cost of HALEU production and provide insights into the major cost drivers affecting total production price.

The following subsections quantify and discuss different cost scenarios, including:

- HALEU production costs (Section 2.3.1)
- HALEU production cost drivers (Section 2.3.2)
- Sensitivity analysis scenarios for HALEU production costs (Section 2.3.3)
- Sensitivity analysis results for HALEU production costs (Section 2.3.4)

2.3.1 HALEU Production Costs

Before HALEU production costs were calculated using the HALEU production cost model, a LEU production cost was calculated to serve as a baseline. This LEU production cost was calculated using the HALEU production cost model inputs that were discussed in in Sections 2.1 and 2.2. This LEU production cost is summarized below in Table 2 for each of the major cost categories. Detailed calculation inputs are provided in Appendix D and the complete calculation is provided in Appendix E.

Table 2. Baseline LEU Production Cost (\$/ kg LEU)

Cost Category	\$/kg	Total Cost %
C_{input}	\$ 1,962	52%
$C_{convert}$	\$ 441	12%
C_{enrich}	\$ 1,223	32%
$C_{deconvert}$	\$ 20	1%
$C_{overhead}$	\$ 119	3%
$\boldsymbol{C_{LEU}}$	**\$ 3,766**	**100%**

The baseline LEU production cost calculated in Table 2 using the methodology and inputs described in this paper is \$3,766 per kilogram of LEU at 4.95% U-235 enrichment. This cost estimate is similar to existing cost estimates for LEU[52] and suggests that the methodology presented can be used to estimate the costs of LEU and HALEU production.

HALEU production costs were also calculated using the cost assumption inputs in the HALEU production cost model. These HALEU production costs (for HALEU enriched to 19.75% U-235 and converted to oxide) are presented for both a 1-step HALEU enrichment process (i.e., where LEU and HALEU enrichment is performed using the same enrichment facility) and a 2-step HALEU enrichment process (i.e., where LEU

[52] WNA | Nuclear Power Economics

and HALEU enrichment is performed in different enrichment facilities with different separative work costs) in Table 3. Detailed calculation inputs are provided in Appendix D and the complete calculation is provided in Appendix E.

Table 3: HALEU Production Cost ($/kg HALEU) for HALEU oxide at 19.75% U-235

Cost Category	Dedicated Process (1-Step)		Separated Process (2-Step)	
	$/kg	**Total Cost %**	**$/kg**	**Total Cost %**
C_{input}	$ 8,120	15%	$ 8,120	34%
$C_{convert}$	$ 1,827	3%	$ 1,827	8%
C_{enrich}	$ 42,520	78%	$ 11,385	48%
→ $C_{enrich\,LEU}$	N/A	0%	$ 5,495	23%
→ $C_{enrich\,HALEU}$	$ 42,520	78%	$ 5,890	25%
$C_{deconvert}$	$ 2,000	4%	$ 2,000	8%
$C_{overhead}$	$ 393	1%	$ 393	2%
$\boldsymbol{C_{HALEU}}$	**$ 54,860**	**100%**	**$ 23,725**	**100%**

The HALEU production costs calculated using the methodology and inputs described in this paper for a 1-step HALEU enrichment process and the 2-step HALEU enrichment process are $54,860 and $23,725 per kilogram of HALEU oxide at an enrichment of 19.75% U-235, respectively. If the HALEU were deconverted to metallic form, the costs would be $56,860 and $25,725 per kilogram of HALEU oxide at an enrichment of 19.75% U-235 based on $2,000 per kgU cost difference between HALEU oxide and metallic deconversion (Section 2.2.3).

The cost difference is driven by the higher cost of separative work completed in new HALEU enrichment facilities compared with existing LEU enrichment facilities (see Section 2.2.2). Maximizing enrichment completed in existing LEU enrichment facilities enables 86% of the separative work (36.63 SWU of the 42.52 SWU needed for enrichment from natural uranium to uranium enriched to 19.75% U-235) can be shifted to enrichment facilities that may have lower enrichment costs.

The 2-step HALEU enrichment process will have significant economic advantages over the 1-step HALEU enrichment process unless HALEU enrichment facilities commercially mature and have costs comparable with LEU enrichment facilities. The remainder of this report will focus on costs associated with a 2-step HALEU enrichment process.

This HALEU production costs estimate for a 2-step HALEU enrichment process can be compared with existing public estimates of HALEU costs, although these estimates are limited. A 2019 report from Euratom targeted a market price of €20,000 ($22,000) per kilogram of metallic HALEU at 19.75% enrichment.[53] Information provided to Euratom from two European enrichment companies (Orano and Urenco) noted that prices at or below a market price of €20,000 ($22,000) per kilogram of metallic HALEU at 19.75% enrichment could be achieved for HALEU production at scale (i.e., greater than 3 MTU per year).

[53] ESA | Securing the European Supply of 19.75% enriched Uranium Fuel

Orano, in particular, noted that prices as low as €12,000 ($13,170) per kilogram of metallic HALEU could have been achievable given "innovative financing solutions".[54]

Comparing the HALEU production cost estimates in this paper to the 2019 cost estimates requires consideration of changing market conditions for LEU fuel cycle activities since 2019. Specifically, uranium feed costs have increased by 250% (approximately $80 / kgU in 2019 to $200 / kgU in 2023) and LEU enrichment costs have increased by 375% (approximately $40 / SWU in 2019 to $150 / SWU in 2023). These market changes are tied to a number of factors including inflationary pressure, changing supply and demand constraints, and international issues such as concern around reliance on Russia for LEU fuels. Using the HALEU production cost methodology in Appendix E, these changes in LEU fuel cycle activities costs would be expected to add approximately $8,900 / kgU to the HALEU production cost. With these additional LEU market costs, the Euroatom estimates range from approximately $22,100 / kgU to $30,900 / kgU. These costs are comparable with the HALEU production costs estimate for a 2-step HALEU enrichment process with deconversion into a metallic form at $25,725 / kgU.[55]

2.3.2 HALEU Production Cost Drivers

Review of the HALEU production costs enables identification of the major cost drivers for HALEU production costs under the baseline assumptions. The HALEU production costs estimate for a 2-step HALEU enrichment process from Table 3 is visualized in Figure 12.

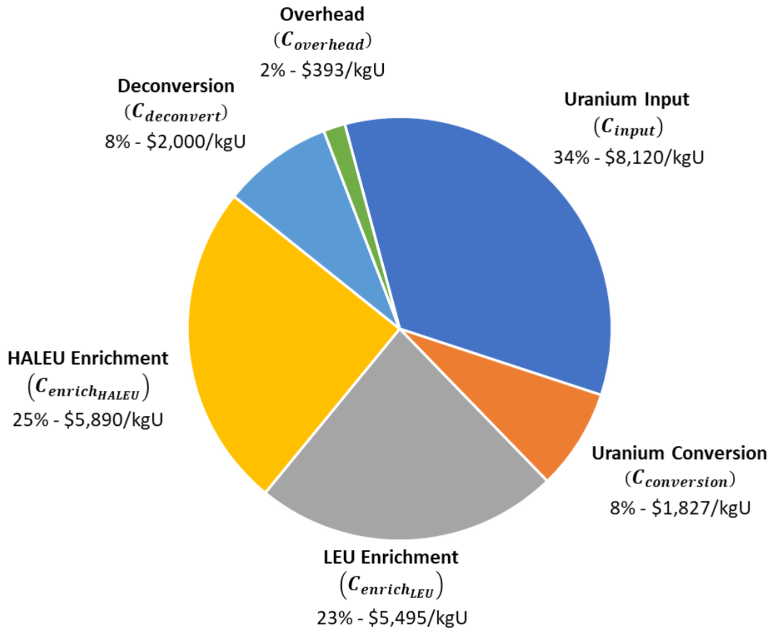

Figure 12. 2-step HALEU enrichment process cost model results

In the baseline HALEU production cost model, LEU fuel cycle related activities represent 65% of the total production costs, driven primarily by uranium mining and input costs (34% of total cost) and LEU enrichment activities (23% of total cost). These activities are not unique to HALEU production and are

[54] ESA | Securing the European Supply of 19.75% enriched Uranium Fuel

[55] An additional $2,000 / kgU is added to the HALEU production cost estimate in Table 3 due to the additional cost of deconverting the HALEU into a metallic form instead of a ceramic form (see Section 2.2.3 for details).

already completed on a commercial basis for existing reactors. These cost drivers will be subject to the existing market forces on uranium production as well as government or commercial considerations related to international uranium markets. The February 2022 Russian invasion of Ukraine has renewed both government and commercial concern about Western reliance on Russian uranium producers.[56] This concern has translated into higher prices for uranium and LEU fuel cycle activities and may result in import restrictions or sanctions intended to drive commercial investment in new Western LEU fuel cycle capacity. Further constraints on Western LEU fuel cycle markets (without commensurate increases in Western LEU production capacity) could significantly impact the cost of HALEU production. Long-term HALEU production cost and price stability will depend on the availability of commercial LEU fuel cycle activities with sufficient production capacity and commodity market forces.

The HALEU-specific production activities are less significant cost drivers in the baseline HALEU production cost model but may be subject to higher variability, especially for near-term production. HALEU enrichment activities (25% of total cost) and HALEU deconversion activities (8% of total cost) will both require new fuel cycle infrastructure and facilities. The cost of activities from these new facilities will be highly dependent on the commercial factors related to their design, licensing, construction, financing, and operation (see Sections 2.2.2 and 2.2.3). As a result, the actual costs for demonstration facilities or other small-scale HALEU production activities could be significantly higher than the baseline HALEU production cost model assumptions – particularly in the near term as new production facilities are brought online. The costs associated with HALEU-specific production activities may be stable and controlled in the long term if HALEU production at scale and long-term contracts can help bring down the per unit enrichment and deconversion costs associated with new facility construction and operation.

2.3.3 HALEU Production Cost Sensitivity Analysis Overview

Uranium market dynamics are complex, and projections of the costs associated with uranium inputs, conversion, enrichment, and deconversion must be included when assessing the HALEU production costs. The baseline assumptions used in this analysis are presented to provide a starting point for discussions on HALEU production costs, but there are significant uncertainties in many of the cost estimates based on limited private or public information on commercial HALEU production costs, and these uncertainties can have large impacts when characterizing HALEU cost drivers and strategies to reduce long-term costs.

For example, increasing demand for HALEU will affect prices for LEU fuel cycle services and products (including uranium mining, conversion, and LEU enrichment), since LEU production is a key process step for HALEU production. Moreover, if DOE or other customers require U.S.-sourced uranium[57], the uranium mining, conversion, and LEU enrichment for HALEU production will have to be performed domestically. This may result in higher HALEU production costs since there is currently only one conversion plant and one enrichment plant in the United States – potentially creating both a supply chain vulnerability and a monopoly pricing risk.

A sensitivity analysis of HALEU production costs provides quantitative insights into these cost variations. For example, increasing the HALEU enrichment cost from $1,000/SWU to $2,000/SWU in the baseline HALEU production cost model for a 2-step HALEU enrichment process would increase the HALEU

[56] Third Way| Western Reliance on Russian Fuel: A Dangerous Game

[57] Requirements on U.S. sourced uranium could be based on policy or commercial considerations to support domestic industrial investment. This term is distinguished from "unobligated uranium" required for specific defense applications which has additional production requirements on use of U.S. origin uranium and enrichment technology.

production cost by nearly $6,000 / kgU at 19.75% enrichment. These cost variations could have significant impacts on both the economic case for advanced reactor operation and the funding requirements to help catalyze investment in new HALEU production capacity (Section 4).

A sensitivity analysis of the HALEU production cost model inputs was performed to help characterize the HALEU cost drivers and provide additional insights on HALEU production costs. The sensitivity analysis was applied to each of major cost components that impact total HALEU production cost (including input cost, conversion costs, LEU enrichment costs, HALEU enrichment costs, and deconversion costs).

Key process unit input cost (e.g., $/SWU) for each cost component in the HALEU production model was varied to assess the change in the HALEU production cost (both absolute and relative). Table 4 summarizes the cost categories, key process unit input cost, baseline values, and sensitivity analysis ranges evaluated in the sensitivity analysis.

Table 4. HALEU Production Cost Sensitivity Analysis Input Ranges

Cost Category	Key Process Unit Input[58]	Baseline Value	Sensitivity Range[59]	
			Lower	Upper
C_{input}	C_F	200 $/kg NU	100 $/kg NU	300 $/kg NU
$C_{convert}$	C_C	45 $/kg NU	25 $/kg NU	65 $/kg NU
$C_{enrich\,LEU}$	$C_{SWU_{LEU}}$	150 $/SWU	100 $/SWU	250 $/SWU
$C_{enrich\,HALEU}$	$C_{SWU_{HALEU}}$	1,000 $/SWU	500 $/SWU	5,000 $/SWU
$C_{deconvert}$	$C_{deconvert}$	2,000 $/kg HALEU	1,000 $/kg HALEU	10,000 $/kg HALEU

[58] Additional details on key process unit inputs are provided in Appendix C.
[59] The cost sensitivity analysis ranges used in this work are not intended to provide a specific range of expected values but are intended to enable readers to quantify the effects of cost category changes on HALEU production costs. A smaller range of costs are considered in this sensitivity analysis for cost categories associated with LEU and production based on the existing commercial market for these products and services. A much larger range of costs are considered in the sensitivity analysis for the costs of HALEU enrichment due to the significant uncertainties associated with the costs of HALEU SWU and the impact of licensing, construction, and financing costs associated with new HALEU enrichment facilities on the enrichment cost paid by HALEU producers.

2.3.4 HALEU Production Cost Sensitivity Analysis Results

A summary of the HALEU production cost sensitivity analysis results is presented in Table 5 for a 2-step enrichment process. Detailed results for the sensitivity analyses are provided in Appendix F.

Table 5. Cost Sensitivity Analysis Results

Cost Category	Change in HALEU Production Cost			
	Lower Bound Change		Upper Bound Change	
	Absolute ($/kg HALEU)	**Percentage of Baseline**	**Absolute ($/kg HALEU)**	**Percentage of Baseline**
C_{input}	($4,060)	-17%	$4,060	17%
$C_{convert}$	($812)	-3%	$812	3%
$C_{enrich_{LEU}}$	($1,832)	-8%	$3,663	15%
$C_{enrich_{HALEU}}$	($2,945)	-12%	$23,560	100%
$C_{deconvert}$	($1,000)	-4%	$8,000	34%

The cost changes presented in Table 5 and detailed in Appendix F would be incremental changes compared with the baseline HALEU production costs of HALEU oxide at 19.75% U-235 using a 2-step process of $23,725 / kgU (Table 3). For example, decreasing the LEU enrichment costs to the upper bound of the sensitivity analysis (e.g., $100 / SWU) would reduce the HALEU production prices by $1,832 / kgU and a result in a HALEU production price of $21,893 / kgU.

Review of the HALEU production cost sensitivity analysis results provide insights on the factors that may have the most significant effects on HALEU production costs and the order of magnitude of these potential effects on final costs.

The first three cost drivers evaluated are the costs associated with LEU production: C_{input} (C_F), $C_{convert}$ (C_C), and $C_{enrich_{LEU}}$ ($C_{SWU_{LEU}}$). Despite these costs making up a large fraction of HALEU production cost (Section 2.3.2), the expected variations in these cost drivers would not likely cause significant changes in HALEU production costs. Increases in these cost categories could increase HALEU production costs by up to 17% depending on the specific cost category increase and the magnitude of the increase. Potential cost increases associated with these cost drivers would also affect the LEU fuel supply chain; HALEU-fueled reactors are not, in principle, any more susceptible to higher LEU production costs.

These cost drivers are subject to uncertainty and volatility in the existing commercial uranium fuel markets. The market reaction and statements by private and public officials following the Russian invasion of Ukraine in 2022 have highlighted the potential impacts of geopolitical events on commercial LEU production. These reactions can ultimately translate into increased costs as market supply is affected by international sanctions, boycotts, or embargos on Russian uranium products or services. This cost volatility, however, is transitory in nature; over the long term, LEU production costs are bounded by capital costs of new and existing production capacity. Ultimately, high LEU production prices due to temporary shortages or trade interruptions will be addressed by new market capital investment based on existing and well characterized market demand for LEU. Characterization of the impacts of LEU production cost drivers (C_{input}, $C_{convert}$, and $C_{enrich_{LEU}}$) is important to help describe potential future price impacts but the effects cannot be mitigated without policy or market changes affecting LEU production.

The next cost driver considered is the cost associated with HALEU enrichment ($C_{enrich_{HALEU}}$). The baseline cost analysis assumes a HALEU enrichment cost of $1,000 / SWU and the sensitivity analysis considers HALEU enrichment costs up to $5,000 / SWU. A larger range of costs is considered in the sensitivity analysis for this cost driver as compared with other cost drivers due to the large uncertainties associated with the costs of HALEU enrichment and the impact of design, licensing, construction, and financing costs associated with new HALEU enrichment facilities (see Section 2.2.2). The wide range of analyzed HALEU enrichment costs illustrates how significant increases in the HALEU enrichment costs can affect HALEU production costs. Characterization of the impacts of HALEU enrichment costs ($C_{enrich_{HALEU}}$) is important to help understand how commercial and programmatic support factors such as enrichment facility output and production facility contract length can affect HALEU production costs.

The final cost driver considered is the cost associated with deconversion ($C_{deconvert}$). The baseline cost analysis assumes a HALEU enrichment cost of $2,000 / kg HALEU and the sensitivity analysis considers HALEU enrichment costs up to $10,000 / kg HALEU. Similar to HALEU enrichment costs, a larger range of costs is considered in the sensitivity analysis for this cost driver as compared with other cost drivers due to the large uncertainties associated with the costs of HALEU deconversion and the impact of design, licensing, construction, and financing costs associated with new HALEU deconversion facilities (see Section 2.2.3). A wider range of analyzed HALEU deconversion costs illustrates the uncertainties related to commercializing HALEU deconversion and the resulting effects on HALEU production costs. Characterization of the impacts of HALEU deconversion costs ($C_{deconvert}$) is important to help understand how commercial and programmatic support factors such as deconversion facility capacity and deconversion service contract length can affect HALEU production costs.

2.4 Summary and Discussion of the HALEU Production Cost Analysis

The HALEU production cost analysis provides several important insights into the cost drivers and sensitivities of commercial HALEU production. The HALEU production cost model assumes a 2-step HALEU enrichment process where natural uranium is enriched in the first step of the process to LEU (up to 4.95% U-235) and then further enriched in the second step of the process to HALEU (Figure *7*).

The major cost drivers for HALEU production under these baseline cost assumptions consist of the costs associated with LEU production required for HALEU production (C_{input}, $C_{convert}$, and $C_{enrich_{LEU}}$). These cost drivers represent 65% of total HALEU production costs. These costs are largely outside the control of HALEU producers and users since their cost dynamics will be dominated by existing international markets. Controlling HALEU production costs therefore requires an understanding of how HALEU production demands will compete with existing demand – both for small HALEU-related LEU demand in the near term that is unlikely to significantly affect LEU production prices and for large HALEU-related LEU demand in the long term that may significantly affect LEU production prices. These market forces will incentivize HALEU producers or end users to secure favorable spot or long-term contracts for uranium feed, conversion services, and LEU enrichment.

The secondary cost drivers for HALEU production under baseline cost assumptions are the higher enrichment services for HALEU production ($C_{enrich_{HALEU}}$). The potential cost differences between LEU and HALEU enrichment are based on existing commercial markets, costs associated with new facility construction and operation, and regulatory requirement differences between production of LEU and HALEU materials. The costs associated with HALEU enrichment are comparable to the costs of LEU enrichment (even assuming a significantly higher HALEU separative work cost compared with LEU separative work costs) due to the smaller amount of separative work required at higher enrichments (36.6 SWU for LEU enrichment compared with 5.9 SWU for HALEU enrichment per kg HALEU).

The final major cost driver for HALEU production under baseline cost assumptions is the deconversion costs ($C_{deconvert}$). The HALEU deconversion costs are subject to significant uncertainty due to the limited experience with HALEU deconversion operations (specifically commercial scale deconversion of HALEU into oxide or metallic forms) and the impact of design, licensing, construction, and financing costs associated with new HALEU deconversion facilities. The HALEU production costs associated with HALEU deconversion may be significant if deconversion facilities cannot be economically operated at small scales, resulting in high per unit deconversion costs. The costs for metallization of HALEU are also likely to be significantly higher than for oxide due to limited industry experience with metal deconversion at scale.

This analysis highlights the importance of LEU fuel cycle activities, HALEU enrichment, and HALEU deconversion to the HALEU production costs. There is substantial uncertainty on the costs associated with deconversion and overhead activities, but these costs may be small compared with the total cost of HALEU production if the commercial costs associated with new facilities and processes can be defrayed across sufficiently large production. The baseline cost estimate of $23,725 / kgU for HALEU should not be treated as a high fidelity estimate of either the short-term or long-term cost of HALEU, but as a starting point for development of more accurate and transparent cost estimates based on improved cost driver information from commercial fuel cycle companies. This methodology and baseline cost estimate serve as a starting point for discussions between policymakers, industry, and other stakeholders on support for domestic HALEU production.

3 Policy Implications of HALEU Production Cost Analysis

The HALEU production cost model in Section 2 provides both methodologies and quantitative results for HALEU production costs that yield insights on the cost drivers associated with HALEU production and programmatic factors that can be used to control or reduce HALEU production costs. There are several key policy implications that are supported by the quantitative and qualitative evaluations performed in this report. The implementation of these policy recommendations can help decrease the cost associated with HALEU production and reduce the operating costs associated with the HAP.

1. **Utilizing a 2-step HALEU enrichment process takes advantage of lower LEU enrichment costs and will reduce HALEU production costs, especially for near-term HALEU production**

The HALEU production cost model highlights that more than six times more separation work is required to enrich uranium from natural uranium to 5% U-235 than to enrich uranium from 5% U-235 to 19.75% U-235 for each kilogram of HALEU produced. LEU enrichment will be cheaper than HALEU enrichment due to existing commercial markets, costs associated with new facility construction and operation, and regulatory requirement differences between production of LEU and HALEU materials. Use of lower-cost LEU enrichment services as part of the HALEU production process significantly reduces the overall cost of HALEU production. If HALEU enrichment facilities can be commercialized and deployed at scale (taking advantage of economies of scale of production and long-term amortization of capital costs), it is possible for long-term HALEU enrichment costs to decline and approach existing LEU enrichment costs.

2. **Ensuring a robust commercial LEU market is key to minimizing HALEU production costs**

The HALEU production cost model estimates that 65% of HALEU production costs under baseline conditions will be dependent on uranium commodity products and fuel cycle services that support existing LWRs. The market for LEU fuel is global and can fluctuate based on challenges and risks to supply and demand. Significant natural uranium (NU) and LEU price fluctuations following major global events such as the shutdown of nuclear power plants after the 2011 Fukushima nuclear accidents, or the 2022 Russian invasion of Ukraine, demonstrate the potential challenges to predictable market behavior. Volatility and increases in LEU prices (mining, conversion, and enrichment) will have a significant direct impact on HALEU prices. Ensuring a robust commercial LEU market using commercial and policy solutions (preferably with U.S. or Western LEU production) is critical to maintaining low and predictable HALEU production costs.

3. **Supporting investment in domestic HALEU and LEU production supply chains is critical to reducing uncertainty in HALEU production costs.**

Investment in new HALEU production capacity is critical to reducing both the cost and cost uncertainties for HALEU production. Ensuring a robust LEU supply chain may require additional investment in domestic LEU infrastructure. The costs associated with HALEU enrichment and deconversion activities will depend significantly on economies of scale for new commercial facilities, with large uncertainties based on commercial arrangements. These costs may be significant for commercial enrichment or deconversion facilities that are first-of-a-kind or have a limited production capacity (e.g., < 10 metric tons of uranium [MTU]/y). Other supply chain activities (i.e., development of transportation infrastructure) without existing commercial customers may benefit from direct or indirect federal support to help ensure availability of these services and to minimize the potential effects on HALEU production costs.

4 HALEU Production Program Evaluations

Prior work by NIA and others has discussed the challenges associated with the development of commercial HALEU fuel cycle infrastructure in the United States. [60, 61, 62, 63, 64] Several papers have proposed programs to catalyze private investment in new domestic HALEU production and create the conditions for success for a sustainable HALEU fuel cycle. These program proposals typically used simplified estimates of total HALEU production costs (often $20,000 - $25,000 per kgU) and simplified models of program operation to quantify total program costs. These simplified cost estimates and models can provide some insights on the order-of-magnitude costs of program support, but do not facilitate more detailed analysis, evaluation, and assessment of different programs that could support commercial fuel cycle development. The goal of DOE's HAP is ultimately to create an initial domestic commercial HALEU production capacity of 10 to 25 MTU per year from two or more private companies.

Two analyses are presented below to provide more detailed insights on the programmatic and appropriation needs to catalyze commercial domestic HALEU production.

The first analysis (Section 4.1) is an updated and expanded evaluation of a previous NIA proposal for a HALEU "material off-take agreement program" in which the federal government makes guaranteed off-take or purchase contracts for HALEU to create a reliable demand signal for commercial investment. In this model, the federal government would provide contracts to private companies for an annual quantity of HALEU production (e.g., MTU/y) at a fixed price ($/MTU) for a fixed period of time (years). These contracts for commercial HALEU producers would create a reliable demand signal for private investment in new HALEU production capacity.

The second analysis (Section 4.2) is a new proposal and detailed evaluation of a HALEU "production services agreements program" in which the federal government makes guaranteed contracts for HALEU production services (e.g., enrichment, deconversion, transportation) as a service to create a reliable demand signal for commercial investment. In this model, the federal government would have a contractual obligation to pay service for a certain amount of work (e.g., SWU/year) at a fixed price (e.g., $/SWU). The contracts for commercial HALEU production services would create a reliable demand signal for private investment in new HALEU production capacity.

Analyses of these two programs provide a clear technical basis for the comparison of different mechanisms for catalyzing private investment in HALEU, evaluation of the costs, benefits, and risks of different programmatic options, and advocacy for authorizations and appropriations required to enable either option.

4.1 HALEU Material Off-take Agreement

Private investment in new commercial HALEU production capacity is currently limited and financially risky because there is significant uncertainty related to the quantity, market price, and timing for market HALEU demands. HALEU material off-take agreements would enable the federal government to create an initial demand signal for HALEU production to incentivize private investment in new capacity. A HALEU material

[60] NIA | Catalyzing a Domestic Commercial Market for High-Assay, Low-Enriched Uranium (HALEU)
[61] NIA | Additional Flexible Funding is Needed to Break Dependence on Russian Nuclear Fuel
[62] NEI | Establishing a HALEU Infrastructure for Advanced Reactors
[63] INL | HALEU Demand and Deployment Options 2020 Workshop Report
[64] Third Way | How Much Does It Cost to Develop New Nuclear Fuel Capacity?

off-take agreement program is analyzed below to quantify its total funding requirements, with sensitivity analyses to evaluate the impact of varying quantity, pricing, and timing factors on program operation requirements.

This section provides descriptions and detailed analysis of a HALEU material off-take agreement program. The major subsections include:

- Description of a HALEU material off-take agreement and major factors that affect program operation and costs (Section 4.1.1)
- Basis and estimates of the major cost drivers for a HALEU material off-take agreement along with ranges of uncertainties considered as part of a sensitivity analysis (Section 4.1.2)
- Description of operational options (revolving fund and a buy-out provision) as part of a HALEU material off-take agreement to limit program costs and risks (Section 4.1.3)
- Evaluation of HALEU material off-take agreement costs under different operational and market conditions (Section 4.1.4)
- Summary of HALEU material off-take agreement costs and policy recommendations (Section 4.1.5)

4.1.1 Material Off-take Agreement Description

HALEU material off-take agreements allow the federal government to make guaranteed off-take or purchase contracts for an annual quantity of HALEU production (e.g., MTU/y) at a fixed price (e.g., $/MTU) for a fixed period of time (years). These contracts for commercial HALEU producers would create a reliable demand signal for private investment in new production capacity. The federal government then transfers or resells the contracts or purchased HALEU material to advanced reactor developers, fuel fabricators, reactor owners, or other buyers. The revenue from these material sales could then be reinvested in the purchase of additional contracted material using a “revolving fund”. The use of a revolving fund reduces the total appropriations necessary for a HALEU material off-take agreement, but the total appropriations required depends on the quantity, price, and timing of purchases and sales.

Four major cost drivers are used to quantify the HALEU material off-take agreement operation costs:

- Cost of HALEU ($/MTU) produced and sold by the program
- Quantity (MTU) and timing (year of production) of HALEU produced by companies supported by the HALEU material off-take agreement program and quantity of HALEU produced by other market participants
- Quantity (MTU) and timing (year of production) of HALEU demand by advanced reactor developers, fuel fabricators, reactor owners, or other buyers
- Fixed and variable costs associated with program operation

Each of these cost drivers may be subject to significant uncertainty due to the variety of highly variable market, policy, and geopolitical factors. Evaluation of program costs requires an assessment of both best estimate values for each cost driver as well as quantification and understanding of how cost driver uncertainty will affect program operations and costs.

4.1.2 Material Off-take Agreement Cost Drivers

Quantifying the costs of HALEU material off-take agreements requires assumptions on the varying quantity, pricing, and timing of HALEU demand and supply, fixed and variable costs associated with program operation, and the use of the revolving fund to reduce program appropriation requirements. For each of these cost drivers, a baseline value is provided based on best estimates for program values and a sensitivity analysis is performed by evaluating a wider range of different input values. The following subsections will discuss each of these cost drivers in more detail.

4.1.2.1 Material Off-take Agreement Production and Sale Costs

The production costs associated with HALEU material off-take agreements are based on the interest of private enrichment companies to invest in new production capacity. The HALEU production cost model described in this paper provides a baseline for production cost estimates for the material off-take agreement and the factors that will affect HALEU production costs. Specifically, existing LEU market dynamics, the amortized cost of new HALEU enrichment facilities, and the use of 1-step or 2-step HALEU enrichment processes can significantly increase the cost of HALEU. Table 6 provides the range of analyzed cost estimates for HALEU production under the HALEU material off-take agreement.

Table 6. HALEU Production Cost Estimate Ranges for Material Off-take Agreement

HALEU Production Cost ($/kgU)
$ 16,000
$ 20,000
$ 24,000
$ 30,000
$ 36,000

A baseline production cost of $24,000 / kgU is used in this analysis for assessments of the costs associated with HALEU material off-take agreements. The baseline production cost is based on the results from the HALEU production model in Section 2. A range of values above and below are also evaluated to quantify the impacts of higher HALEU production costs (e.g., due to increases in one or more cost drivers discussed in Section 2.3) on total appropriations requirements to sustain the material off-take program.

The net program cost associated with a HALEU material off-take agreement are based on the ability of the federal government to transfer or resell the contracts or purchased HALEU material to advanced reactor developers, fuel fabricators, reactor owners, or other buyers. Characterizing the sales costs for HALEU procured under HALEU material off-take agreements is difficult because of the market conditions that could impact sale prices. In principle, the HALEU sale price could either be equal to the production cost (sale at cost), below the production cost (sale at discount), or above the production cost (sale at mark-up). Each of these sale conditions would affect the total funding needed to support program operations.

In this evaluation, it is assumed that the HALEU would be sold at cost to minimize taxpayer burden under typical market conditions but could be sold at discount if the government purchase price is significantly higher than the market value of the HALEU at the time of sale. This option would enable the program to both reduce HALEU stockpiles and help ensure market HALEU supply at competitive prices. As a result, three sale conditions are considered to evaluate the effects on program costs:

- Sale at cost (sale price equal to production price)
- Sale at slight discount (sale price is equal to 80% of production price)
- Sale at steep discount (sale price is equal to 60% of production price)

Sale at cost is considered as the baseline assumption in the program analysis due to a supply- constrained HALEU production market. Under current market demand conditions, it is unlikely that domestic HALEU production would have to be significantly discounted to facilitate sales unless the available HALEU production price was excessively high (e.g., 2-3 times existing expected market prices).

4.1.2.2 HALEU Production Quantity and Timing

The annual HALEU production quantity for HALEU material off-take agreements is based on the expected supply constraints and the expected demand needs.

The supply constraints are based on the production amount needed to justify private investment in new production capacity. New uranium enrichment facilities have fixed upfront and operating costs that do not scale based on the output or production of the facility. Increasing the production output of the facility results in a lower average long-term price for enrichment services (e.g., MTU of production or $/SWU). This results in a production versus unit cost curve for new enrichment facilities. Enrichment companies would likely have a minimum production quantity or facility output (MTU/y or SWU/y) required to justify the fixed costs, capital investment, and commercial risk associated with construction and operation of new facilities.

HALEU demand is based on the expected HALEU needs for commercial advanced reactor projects. The U.S. DOE has made significant investments in advanced reactors that require HALEU through ARDP and other federal programs. While the federal government should not be expected to support production that meets 100% of expected HALEU demand from these projects, the program supply should be sufficient to fuel initial federally supported demonstration reactors and catalyze sufficient private investment to create a sustainable commercial domestic HALEU market. This translates into providing sufficient supply in the near term to support first movers and creating sufficient assured market supply of HALEU to enable long-term investment in new advanced reactor projects, thus creating a market demand signal that drives additional private investment in HALEU production.

HALEU production timing is also critical to support both HALEU enrichment companies and advanced reactor companies. Multiple advanced reactor developers have announced plans to demonstrate advanced reactors in the next five years that will require HALEU and major projects such as the ARDP demonstration award winners (TerraPower and X-energy) are expected to deploy their demonstration reactors in the late 2020s or early 2030s. HALEU UF_6 could be needed by commercial projects up to two years before reactor operation to allow time for deconversion, fuel fabrication, testing, transportation, and fuel loading into the reactor. Supporting advanced reactor demonstrations this decade, therefore, requires HALEU availability as soon as 2026. Satisfying commercial needs for HALEU, however, is constrained by the timelines associated with the construction and start-up of new HALEU production facilities. The design, licensing, and construction of new enrichment and processing facilities capable of producing HALEU can reportedly take three to five years depending on the company and funding availability. These limitations are driven by both administrative processes such as site licensing and permitting and the manufacturing of highly specialized enrichment equipment (typically gaseous centrifuges) used for uranium enrichment. Thus, increased production of HALEU in significant quantities before 2026 is unlikely given existing market constraints.

Existing studies of HALEU production and market constraints on HALEU suppliers suggest that guaranteed federal purchase of 25 MTU of HALEU per year would be sufficient to support private investments by at least two enrichment companies in new HALEU production capacity. This baseline production of 25 MTU per year is used in this analysis and is assumed to start in 2028 for a period of 10 years. The 10-year period is based on discussions with enrichment companies who stated that a 10-year guaranteed off-take contract would be sufficient demand and guaranteed production to support private capital investment in new HALEU enrichment facilities that could operate for 30 or more years.

It is important to note that the duration and timing of the material off-take agreement program proposed and evaluated in this section differs from the current DOE proposals for the HAP. The enabling legislation for the HAP provides the DOE programmatic authority for the HAP through September 30, 2034.[65] The DOE's June 2023 draft Request for Proposal for HALEU enrichment assumed a "10-year period of performance" for the completion of HALEU enrichment activities.[66] These programs, however, do not account for the time required for the design, licensing, construction, and commissioning of HALEU enrichment and deconversion facilities. Enrichment companies have stated that new HALEU enrichment infrastructure will take 4-7 years to begin production. As a result, the current program design may only allow 3 - 6 years of material production under expected commercial deployment timelines. This shortened contractual production period may substantially increase the costs associated with HALEU production as companies seek to amortize capital costs over a shorter period. This program evaluation considers a 10-year production period after construction to create more favorable program terms but amendments to the Energy Act of 2020 would be required to enable this program timing.

In addition to HALEU production catalyzed by HALEU off-take agreements, it is assumed that fully privately financed commercial HALEU production would emerge in the mid-2030s to support growing demand for HALEU based on widescale deployment of advanced reactors. This production is assumed to gradually increase based on expected forward contracts for HALEU delivery in the late 2030s and beyond. The timing and quantity of privately funded HALEU production capacity would vary based on the expected demand from advanced reactor developers, fuel fabricators, reactor owners, or other buyers.

It is also possible, however, that there is no additional commercial demand for HALEU due to limited deployment of advanced reactors using HALEU fuel so there is no private investment in new or continued HALEU production. As a result, HALEU production would consist of the contracted HALEU production period but would be scaled back or halted after the contract period with no additional private commercial investment. In a worst-case scenario, HALEU production would be completely halted due to lack of commercial market demand for HALEU and a build-up of government HALEU stockpiles.

The production schedule for HALEU production from both program-supported and fully private supported producers is summarized in Table 7. Three different production schedules for fully privately supported producers are provided: a baseline production schedule, a slow escalation schedule where the incremental increases in production are delayed based on slower demand increases, and no additional production schedule where HALEU production is halted after the program contract period.

[65] Energy Act of 2020 - Section 16281
[66] DOE | Acquisition of High-Assay Low-Enriched Uranium - Enrichment - Draft RFP

Table 7. HALEU Production Schedule for Baseline, Slow Escalation, and No Additional Private Production Schedule

FY	Baseline Annual HALEU Production (MTU/y)			Slow Escalation Annual HALEU Production (MTU/y)			No Additional Annual HALEU Production (MTU/y)		
	Program Supported Production	Private Commercial Production	Total Production	Program Supported Production	Private Commercial Production	Total Production	Program Supported Production	Private Commercial Production	Total Production
2023	0	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0	0
2028	25	0	25	25	0	25	25	0	25
2029	25	0	25	25	0	25	25	0	25
2030	25	0	25	25	0	25	25	0	25
2031	25	0	25	25	0	25	25	0	25
2032	25	0	25	25	0	25	25	0	25
2033	25	0	25	25	0	25	25	0	25
2034	25	25	50	25	0	25	25	0	25
2035	25	50	75	25	0	25	25	0	25
2036	25	75	100	25	0	25	25	0	25
2037	25	100	125	25	0	25	25	0	25
2038	0	225	225	0	25	25	0	0	0
2039	0	250	250	0	50	50	0	0	0
2040	0	275	275	0	75	75	0	0	0
2041	0	300	300	0	100	100	0	0	0
2042	0	325	325	0	125	125	0	0	0

The three HALEU production schedules in Table 7 are used as the basis for evaluation of program operation and program appropriations requirements. Other production schedules (including accelerated or expanded private commercial HALEU production) are possible based on private customer contracts for HALEU off-take or direct investment in new production facilities. These schedules would represent successful implementation of the HAP (i.e., catalyzed private investment in new HALEU production capacity) and would align closely with program goals and operation. These alternative production schedules are thus bounded by the operational analysis performed in this paper and not evaluated in further detail in this analysis.

4.1.2.3 HALEU Demand and Sale Quantities and Timing

The demand and sale quantities associated with a HALEU material off-take agreement are based on the expected commercial demand for HALEU and the interactions between HALEU material off-take agreement sales and fully private commercial sellers. The HALEU demand and sale quantity in this analysis is divided into two categories: HALEU demands from DOE ARDP-supported projects and HALEU demands from other commercial reactor deployments. The HALEU demand from the ARDP-supported projects is assumed to be 6 MTU per year starting in 2028. This demand is based on an estimated quantity to support core reloads and other fuel activities for the two demonstration reactors (TerraPower and X-energy) and an additional 1-2 MTU per year to support other ARDP-sponsored research and development programs.[67]

The ARDP demand does not include the HALEU fuel requirements associated with their initial reactor core fuel load for the ARDP demonstrations or other future demonstration reactors. Due to the timing associated with the construction and commissioning of new HALEU production facilities, it is assumed that an alternative HALEU source will be required to provide HALEU for the first reactor core fuel load for each reactor and ARDP fuel programs before 2028. Near-term sources of HALEU may include the recovery of HALEU from prior previous DOE fuel programs and downblending of excess high-enriched uranium (HEU) from DOE stockpiles (see Appendix A for discussion on near-term alternative HALEU pathways).

The HALEU demand from other commercial reactor deployments is more challenging to estimate than the ARDP-supported projects because it depends on both the magnitude and timing of HALEU-fueled advanced reactor deployments. The actual deployment of these reactors will heavily depend on the construction and operational performance of demonstration reactors, federal and state policies related to clean energy deployment, and the actual cost and deployment timelines of new reactors. Three representative cases are analyzed to provide insights on the operation and performance of the HALEU material off-take agreement under different demand conditions:

- baseline HALEU demand (deployment of HALEU advanced reactors based on prior INL estimates of HALEU demands to support 2050 net zero goals[68])
- slow escalating HALEU demand (delayed deployment of additional advanced reactors following the initial ARDP demonstration reactors)
- no demand beyond ARDP (no deployment of additional advanced reactors following the initial ARDP demonstration reactors and ARDP sponsored research and development programs)

These three representative cases provide insights on the operation and performance of the HALEU material off-take agreements and the resulting impact on program appropriations requirements. The slow escalating case approximates delayed and reduced demand for HALEU based on an assumed delay in the deployment of advanced reactors and is provided to help quantify the impacts of demand delay on program operation and appropriations requirements. The demand schedule for HALEU production for the three HALEU demand cases is presented in Table 8 and visualized in Figure 13. These demand schedules are used as the basis for evaluation of program operation and program appropriations requirements.

These demand schedules are lower that previous industry estimates of future HALEU demand based on surveys of advanced reactor developer deployment plans.[69] The HALEU demand projections provided by industry would represent both a rapid and significant deployment advanced nuclear energy in the early 2030s. The new enrichment capacity required to meeting the Nuclear Energy Institute (NEI) demand estimate of 500 MTU of HALEU in 2035 (approximately 20,000 kSWU) would be comparable to current

[67] ARDP related HALEU demands are based on average core reload demands of approximately 2 MTU per year for the X-energy project and 2.5 MTU per year for the TerraPower project based on publicly available reactor performance information. An additional demand of approximately 1.5 MTU per year is assumed to support fuel development and qualification activities by other ARDP funding recipients. These reactor fuel demand estimates are intended as order of magnitude estimates to help predict overall HALEU market demands and are not indictive of the predicted performance, economics, or operational characteristics of the ARDP demonstration reactors.

[68] INL | Estimated HALEU Requirements for Advanced Reactors to Support a Net Zero Emissions Economy by 2050

[69] NEI | Updated Need for HALEU

LEU enrichment capacity across Western countries (approximately 26,000 kSWU).[70] If the scale of deployment and resulting HALEU demand is confirmed through firm contracts in the early 2030s, private markets may be able to provide the capital needed to finance the expansion of HALEU production facilities to meet mid-decade production needs. As a result, the INL estimates of HALEU demands are used as a more conservative baseline demand estimate to support the design and analysis for HALEU material off-take agreements.

It is also assumed that HALEU sale operations as part of the HALEU material off-take agreements is structured to minimize competitive impacts on private HALEU markets. The analysis of HALEU material off-take agreements assumes that HALEU sales will only occur if the HALEU is not available from private production. The HALEU sale program can only sell an amount of HALEU equal to or less than the difference between the annual HALEU demand and the private commercial HALEU production. This is intended to limit market interference by the federal HALEU material off-take agreements and reduce the likelihood that sales under the HALEU material off-take agreements will inadvertently suppress market demand signals by providing a source of government- subsidized HALEU. Specific programmatic and operational mechanisms to minimize market interference would need to be developed in discussions with HALEU producers, HALEU users, and other stakeholders.

However, it is likely that customers will agree to secure multiple years of HALEU at a time when making purchases and not simply purchase materially annually on an "as produced" basis. This contracting process would ensure a more secure supply of HALEU to support both fuel fabrication and operation. It is reasonable to expect that since additional private production would require additional capital investment, supply from federal material off-take agreements is likely to be committed before substantial additional private supply is even available. It is unlikely that new privately supported commercial HALEU production would significantly displace supply from the off-take program in the early stages.

[70] WNA | Global and Western Uranium Enrichment Capacity

Table 8. HALEU Demand Schedule for Baseline, Slow Escalation, and No Demand Schedule

FY	Baseline Annual HALEU Demand (MTU/y)			Slow Escalation Annual HALEU Demand (MTU/y)			No Escalation Annual HALEU Production (MTU/y)		
	ARDP Demand	Private Demand	Total Demand	ARDP Demand	Private Demand	Total Demand	ARDP Demand	Private Demand	Total Demand
2023	0	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0	0
2028	6	0	6	6	0	6	6	0	6
2029	6	0	6	6	0	6	6	0	6
2030	6	15	21	6	0	6	6	0	6
2031	6	15	21	6	12	18	6	0	6
2032	6	30	36	6	12	18	6	0	6
2033	6	40	46	6	12	18	6	0	6
2034	6	60	66	6	12	18	6	0	6
2035	6	70	76	6	12	18	6	0	6
2036	6	100	106	6	12	18	6	0	6
2037	6	110	116	6	30	36	6	0	6
2038	6	225	231	6	30	36	6	0	6
2039	6	250	256	6	60	66	6	0	6
2040	6	275	281	6	60	66	6	0	6
2041	6	300	306	6	120	126	6	0	6
2042	6	325	331	6	200	206	6	0	6

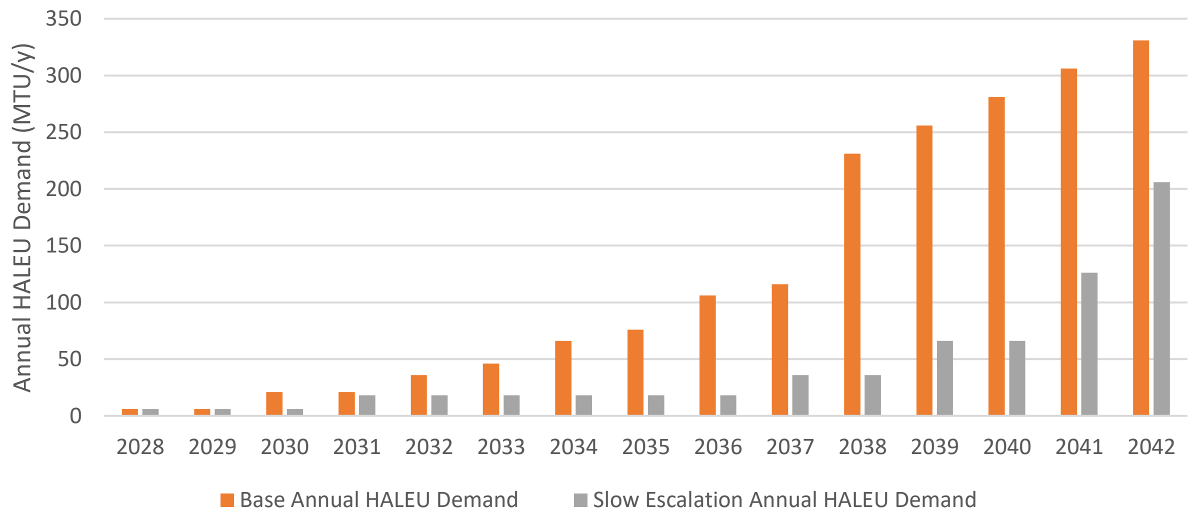

Figure 13. HALEU Demand Schedule for Baseline and Slow Escalation Demand Schedules

4.1.2.4 Material Off-take Agreement Fixed and Variable Costs

DOE's fixed and variable costs associated with program operation, management, and overhead are included as an important assumption in the operation of a HALEU material off-take agreement program as these costs cannot be recouped into the program's funds by the sale of HALEU using a revolving fund. Two major costs are considered in the program: fixed costs associated with initial program operation, and the variable costs associated with HALEU transportation and storage.

- *Fixed costs associated with initial program operation:* Development of new HALEU production facilities requires up-front funding to support design, licensing, and long-lead component orders. These costs are incurred years before HALEU production and will increase the final per unit cost of HALEU production if interest on these costs must be paid before operation. Federal funding support for up-front costs can help reduce overall HALEU production costs. A baseline cost assumption of $50 million per year for two enrichment companies ($100 million total per year) is assumed for the first two years of program operation ($200 million total in fixed operational costs).[71] This funding could support initial design and licensing activities to accelerate the deployment of new production capacity and satisfy HALEU production goals. This cost assumption can be revised for different levels of federal support to assess the impact on overall program operation costs and appropriations requirements. Some companies may have already completed program-related preparation work at their own risk and would not need to spend two years to prepare facility design documents or complete licensing activities.
- *Variable costs associated with HALEU transportation and storage:* Production of HALEU for advanced reactors will require additional transportation and storage activities, especially if the material is produced by a commercial enrichment company but not used by a fuel producer for months or years after production. As a result, there are variable costs that scale with the quantity of HALEU associated with these activities that may not be recouped by the subsequent HALEU sale. In this analysis, an additional cost of $500,000 per metric ton of HALEU stockpiled is included per year to account for additional transportation and storage costs that would not be included in the initial production cost.[72]

These cost factors are intended primarily as order of magnitude estimates that help characterize and quantify program costs and operation.

4.1.3 Material Off-take Agreement Cost Operational Options

Program operation costs and appropriations requirements for HALEU material off-take agreements are assessed for a variety of input assumptions and operational assumptions. The effects of two program operational options are evaluated in addition to the sensitivity analysis on cost drivers. The two program operational options focus on minimizing the program costs and appropriations requirements under a variety of different market conditions:

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[71] The assumed fixed cost of $100 million per facility is based on preliminary discussions with enrichment providers during the DOE HALEU RFP development process. These values may be higher or lower depending on company and project specific needs.

[72] The assumed additional cost of $500,000 per metric ton of HALEU per year ($500/kg/y) is likely high based on prior studies of advanced nuclear fuel cycle costs (2017 INL Advanced Fuel Cycle Cost Basis) but reflects the uncertainty associated with cask and storage facility availability for HALEU. This assumption represents a reasonable upper bound estimate for variable program costs.

- Revolving fund: revenue from the sale of HALEU to advanced reactor developers, fuel fabricators, reactor owners, or other buyers is returned to the program to support subsequent purchases of HALEU and program operation
- Negotiated contract buy-out: the program will have the option to prematurely stop purchase contracts by paying an annual fee equal to a portion of the contract for the remainder of the original HALEU off-take agreement

These two operational options for the program help to reduce the overall program costs and appropriations requirements if there are significant variations in market conditions.

The revolving fund allows the program to use revenue from HALEU sales to fund subsequent program activities. The revolving fund allows the program to effectively purchase a larger quantity of HALEU with a smaller initial appropriation. The use of the revolving fund is beneficial for the taxpayer and reduces the program appropriation burden, but also makes the program more dependent on the timing and sale price of HALEU that is sold by the program. If HALEU sales are delayed too significantly after the HALEU purchase (with no HALEU sales beyond ARDP in a bounding case) or if the sale price is significantly below the purchase price, the total program costs would converge to the cost of program operation without the revolving fund. The program operation costs and appropriations requirements are assessed for the program both with and without a revolving fund, and for different supply and demand schedules that can affect requirements on the initial size of the revolving fund to maintain a positive balance.

Across the government, revolving funds are also intended to focus management and supplier attention on program revenues and expenditures through business-like programming, planning and budgeting. This can create cost-control incentives, similar to those that exist in the private business sector, thereby encouraging efficiencies and ultimately yielding taxpayer benefits.[73] However, the analysis in this paper did not attempt to estimate these potential benefits or presume they would be realized.

Negotiated contract buy-outs allow the program to prematurely end HALEU purchase contracts. A buy-out could be used in cases where the commercial HALEU demand is significantly lower or slower than anticipated (e.g., delays beyond the slow escalation demand schedule) or the commercial HALEU demand does not increase (beyond the initial ARDP demonstration reactors and the ARDP-sponsored research, development and deployment programs). DOE may not want to continue purchasing, transporting, and storing HALEU that is not needed by commercial buyers, or the program sales may have been effectively replaced by private HALEU producers on the market. As a result, it would be prudent for the program to halt purchases, but DOE must fulfil the contractual obligation with HALEU producers that were used as a basis for private financing contracts. A negotiated contract buyout would enable the program to pay an annual fee to the HALEU producer that is equal to a fixed percentage of the original value of the HALEU off-take contract. This fixed percentage could be negotiated by the HALEU producer based on the expected revenue directly associated with HALEU enrichment and deconversion facilities that were constructed to support HALEU production. After the buy-out, the HALEU producer would have no contractual obligation to the program to produce material and would be free to use their production facilities for other commercial purposes.

[73] GAO | Appropriations Law Volume III (GAO-09-978SP)

A negotiated contract buy-out could be structured using several different factors including:

- percentage of the contract value buy-out
- duration of the contract buy-out (one-year, multi-year)
- type of contract buy-out (year-by-year, remainder of contract)

The baseline assumptions in this analysis of the HALEU material off-take agreements are:

- 40% contract buy-out value (based on an upper end approximation of HALEU enrichment costs, deconversion costs, and administrative costs associated with HALEU production)[74]
- 5-year contract buy-out for the second half of a HALEU production contract

These contract buy-out conditions could be varied based on negotiations with HALEU producers to assess the conditions that would catalyze private investment in new production facilities.

It is important to note that if the negotiated contract were based solely on HALEU enrichment service costs and could be exercised on a year-by-year basis, the program would effectively converge with the HALEU enrichment service agreement structure described below.

4.1.4 Material Off-take Agreement Cost Evaluation

Program operation costs and appropriations requirements for a HALEU material off-take agreement were quantified under the variety of input assumptions and operational assumptions previously discussed. The program costs were quantified by performing a year-by-year evaluation of HALEU purchases, sales, and fixed and variable program costs based on assumed production and demand schedules. In some cases, a revolving fund or contract buy-out mechanism may be used to reduce the overall costs of program operation.

The following subsections provide descriptions and discussion on each of these costs. A summary of the different HALEU material off-take agreement cost assessments and policy implications of the assessments are provided in Section 4.1.5. The full year-by-year program cost assessments are provided in Appendix H.

4.1.4.1 Baseline Program Cost Analysis with and without a Revolving Fund

The baseline cost analysis is based on the following input conditions:

- baseline production schedule (Table 7)
- baseline demand schedule (Table 8)
- HALEU purchase price of $24,000 / kgU ($24 million per MTU)
- HALEU sale price of 100% of the purchase price

The baseline cost analysis for the HALEU material off-take agreement is conducted both with and without the use of a revolving fund to quantify the impact on program appropriations requirements. Table 9 summarizes the program operating costs and appropriation requirements for the baseline cost analysis with and without the use of the revolving fund. Figure 14 shows the annual HALEU purchases, HALEU

[74] The specific buyout percentage would be based on the payments needed to ensure that companies constructing new infrastructure to support HALEU production (i.e., HALEU enrichment facilities and HALEU deconversion facilities) could fully recover their infrastructure investments plus interest and return on capital. This assurance enables companies to raise the necessary capital to support new facility design, construction, and operation.

sales, and program costs for the baseline case (left axis) as well as the net cumulative program expenditures with and without the use of the revolving fund (right axis).

Table 9. Program operating costs and appropriations requirements for baseline cost analysis

Operation Assumption	Total Material Purchased (MTU)	Total Program Expenditures ($M)	Unrecovered Program Expenditures ($M)	Total Appropriations Requirement ($M)
No Revolving Fund	250	$ 6,297.0	$ 297.0	$ 6,297.0
Revolving Fund	250	$ 6,297.0	$ 297.0	$ 1,376.5

This baseline cost analysis provides two important insights into the operation of the HALEU material off-take agreement. First, the use of the revolving fund would not directly impact the total material purchased, the total program expenditures, or the net program expenditures (excluding potential efficiency benefits of revolving fund operation). In both cases, the program will have total expenditures of approximately $6.3 billion to produce, store, transport, deconvert, and deliver 250 MTU of HALEU (based on the sum of all HALEU purchases and operating costs). Both cases would have net program expenditures of approximately $300 million associated with up-front costs, and HALEU storage and transportation costs (based on the sum of all the operating costs). These are costs ultimately paid by the taxpayer as part of DOE program operation, management, and overhead, and cannot be recovered using at-cost material sales.

Second, the use of a revolving fund has a significant impact on the appropriations requirements for the HALEU material off-take agreement (Figure 14). If a revolving fund is not used, the total appropriations must be equal to the total program expenditures (approximately $6.3 billion) because any revenue generated from HALEU sales would be returned directly to the U.S. treasury. If a revolving fund is used, revenue from HALEU sales can be used to support subsequent program purchases so the total appropriations is equal to the maximum cumulative expenditures of the HALEU material off-take agreement. Figure 14 illustrates that the maximum cumulative expenditure would occur during 2031 in the baseline cost analysis (based on HALEU demand exceeding HALEU production directly supported by the off-take agreements). The program would require total upfront appropriations of $1.4 billion to remain operational throughout the program's planned duration using the revolving fund.

This analysis demonstrates that the use of a revolving fund for a HALEU material off-take agreement does not directly affect the total program operation costs or material purchases but has a significant impact on the total appropriations requirements for the HALEU program. Use of the revolving fund can help taxpayers by reducing the appropriations requirements needed to support HALEU material off-take agreement operation, and potentially though encouraging more economically efficient program management and operation.

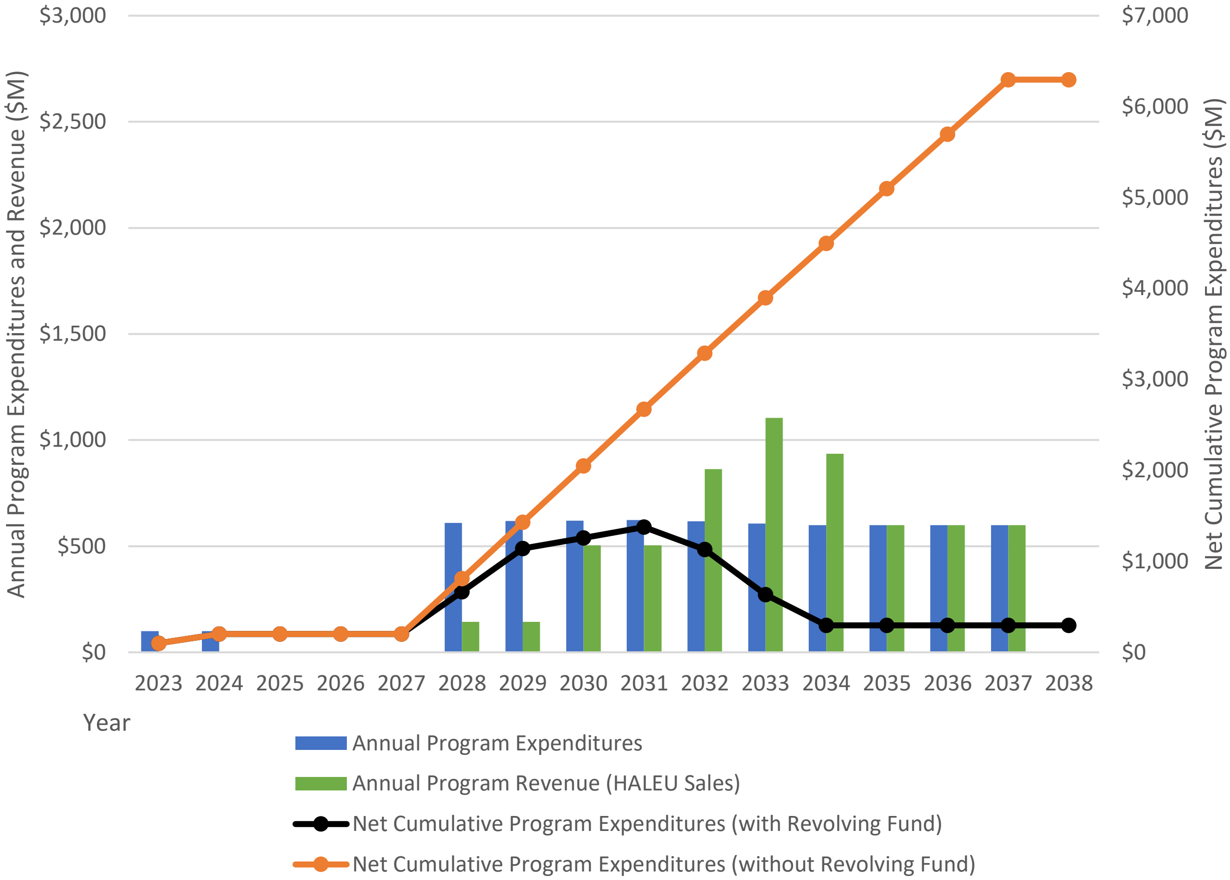

Figure 14. Annual revenue and cumulative expenditures for baseline HALEU material off-take agreement

4.1.4.2 Baseline Program Cost Sensitivity Analysis with and without a Revolving Fund

A sensitivity analysis on the baseline cost analysis is performed to evaluate the impact of varying HALEU purchase prices on the total program operating costs and appropriations requirements. The sensitivity analysis is performed based on the following input conditions:

- baseline production schedule (Table 7)
- baseline demand schedule (Table 8)
- varying HALEU purchase price from $16,000 / kgU to $36,000 / kgU ($16 million per MTU to $36 million per MTU)
- HALEU sale price of 100% of the purchase price

The baseline cost sensitivity analysis for the HALEU material off-take agreement is conducted both with and without the use of a revolving fund to reduce program operational and appropriations requirements. Table 10 summarizes the program operating costs and appropriation requirements for this sensitivity analysis. Figure 15 shows the total appropriations requirements for each HALEU purchase price with and without the use of a revolving fund.

Table 10. HALEU purchase price cost sensitivity analysis for total appropriations requirements with and without use of a revolving fund

HALEU Purchase Price ($M/MTU)	Total Material Purchased (MTU)	Net Program Expenditures ($M)	Total Appropriations Requirement without Revolving Fund ($M)	Total Appropriations Requirement with Revolving Fund ($M)
$ 16.0	250	$ -297.0	$ 4,297	$ 1,009
$ 20.0	250	$ -297.0	$ 5,297	$ 1,193
$ 24.0	250	$ -297.0	$ 6,297	$ 1,377
$ 30.0	250	$ -297.0	$ 7,297	$ 1,653
$ 36.0	250	$ -297.0	$ 9,297	$ 1,929

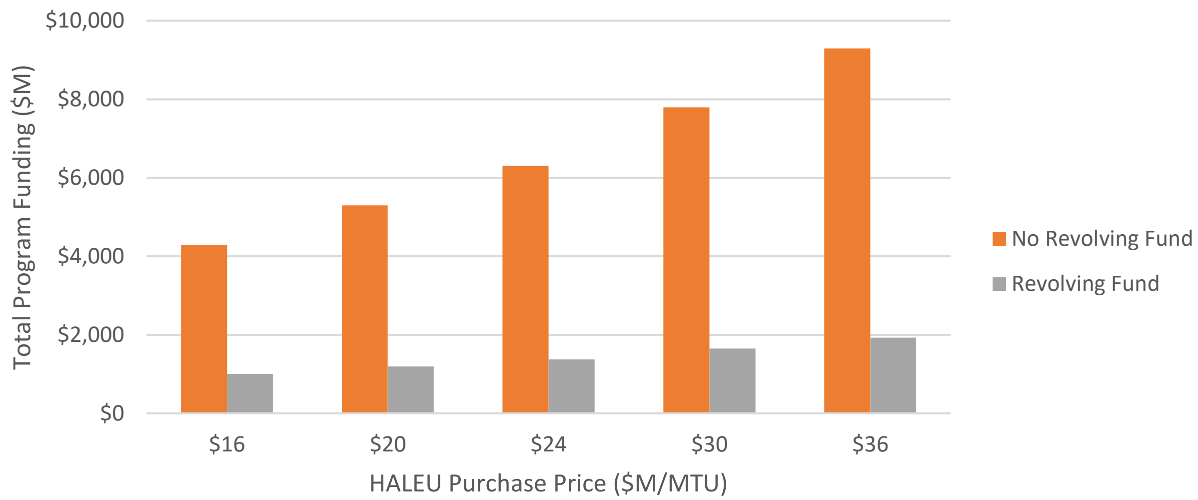

Figure 15. Total appropriation requirements for baseline program cost analysis with and without use of a revolving fund for different HALEU purchase prices

The sensitivity analysis on the baseline cost analysis for the HALEU material off-take agreement also provides two important insights into the operation of the HALEU material off-take agreement. First, assuming equal purchase and sale prices for HALEU results in net program expenditures of $297 million associated with up-front costs and HALEU storage and transportation costs for all HALEU prices. These costs are based on the quantity and timing of purchases and sales and do not vary based on HALEU prices. As a result, the net program expenditures are constant for all HALEU purchase prices.

Second, the use of a revolving fund has a significant impact on the appropriations requirements for the HALEU material off-take agreement for any HALEU purchase cost. Not using a revolving fund can significantly increase appropriations requirements for higher HALEU production costs. Using the baseline production and demand schedules and equal production and sale costs, the use of a revolving fund reduces the appropriations requirements for the HALEU material off-take agreement by approximately 75% to 80% depending on the specific HALEU production cost. However, it is important to note that use of a revolving fund to reduce appropriation requirements also necessitates use of a buyout option (Section 4.1.3). Without a buyout option, the appropriations would be too low to guarantee contractual obligations and any off-take contract would becomes subject to the same uncertainty facing existing markets: that commercial sales of HALEU cannot support new investment.

4.1.4.3 Baseline Program Cost Sensitivity Analysis with Varying Production and Demand Schedules

A sensitivity analysis on the baseline cost analysis is performed to evaluate the impact of varying HALEU production and demand schedules on the total program operating costs and appropriations requirements. The sensitivity analysis is performed based on the following input conditions:

- baseline, slow escalating, and no production schedules (Table *7*)
- baseline, slow escalating, and no demand schedules (Table *8*)
- varying HALEU purchase price from $24,000 / kgU to $30,000 / kgU ($24 million per MTU to $30 million per MTU)
- HALEU sale price of 100% of the purchase price

The baseline cost sensitivity analysis for the HALEU material off-take agreement is evaluated to consider the program operation and appropriation requirements for varying production and demand schedules at different HALEU purchase prices and the impacts of a negotiated buy-out for the no-production and no-demand schedule cases. Table 11 summarizes the program operating costs and appropriation requirements for this sensitivity analysis for the four analyzed cases at the HALEU purchase price of $24 million per MTU while Table 12 summarizes the costs and requirements for the four analyzed cases at a HALEU purchase price of $30 million per MTU.

Table 11. HALEU production and demand schedule sensitivity analysis for total appropriations requirements with and without use of a revolving fund at $24M/MTU purchase price

Sensitivity Case	Total HALEU Purchased (MTU)	Total Appropriations Requirement without Revolving Fund ($M)	Total Appropriations Requirement with Revolving Fund ($M)	Net Program Expenditures in FY42 ($M)	Unsold Inventory in FY42 (MTU)	Unsold Inventory Value in FY42 ($M)	Net Program Value in FY42 ($M)
Baseline Production and Demand	250	$ 6,297	$ 1,377	($297)	0	$0	($297)
Slow Escalating Production and Demand	250	$ 6,572	$ 2,878	($572)	0	$0	($572)
No Production and Demand	250	$ 7,153	$ 5,283	($4,993)	160	$3,840	($1,153)
No Production and Demand (with buy-out)	125	$ 4,853	$ 3,295	($2,693)	35	$840	($1,853)

Table 12. HALEU production and demand schedule sensitivity analysis for total appropriations requirements with and without use of a revolving fund at $30M/MTU purchase price

Sensitivity Case	**Total HALEU Purchased (MTU)**	**Total Appropriations Requirement without Revolving Fund ($M)**	**Total Appropriations Requirement with Revolving Fund ($M)**	**Net Program Expenditures in FY42 ($M)**	**Unsold Inventory in FY42 (MTU)**	**Unsold Inventory Value in FY42 (MTU)**	**Net Program Value in FY42 ($M)**
Baseline Production and Demand	250	$ 7,797	$ 1,653	($297)	0	$0	($297)
Slow Escalating Production and Demand	250	$ 8,072	$ 3,472	($572)	0	$0	($572)
No Production and Demand	250	$ 8,653	$ 6,423	($5,953)	160	$4,800	($1,153)
No Production and Demand (with buy-out)	125	$ 5,903	$ 3,985	($3,203)	35	$1,050	($2,153)

The sensitivity analysis of varying production and demand schedules for the HALEU material off-take agreement provides three important insights into the operation of the HALEU material off-take agreement.

The first major insight from Table 11 is that a slowly escalating or delayed production and demand schedule has a minimal impact on the total program costs and appropriations requirements without a revolving fund but has a significant impact on the appropriations requirements with the revolving fund. The slight increase in the total appropriations requirement without the revolving fund ($6.3 billion for baseline case compared with $6.5 billion for slow escalating case in Table 11) is due to the accumulation of costs related to storage of larger quantities of purchased HALEU purchased for a longer duration before sale. A much larger increase is required between the two cases, however, for the total appropriations requirement with the revolving fund ($1.4 billion compared with $2.9 billion). This large difference is due to the need for additional appropriations to make HALEU purchases before the revenue from delayed sales can be used to support HALEU purchases. This insight is also true for the increased HALEU production cost summarized in Table 12.

Figure 16 illustrates the impact of the slow escalating demand schedule on the total appropriations requirement with the revolving fund. Uncertainty and delay in HALEU demand has a significant impact on the total program appropriations if a revolving fund is used to reduce total cost. This conclusion is consistent for all HALEU production prices although the magnitude of the appropriations requirement difference will increase with the HALEU production price.

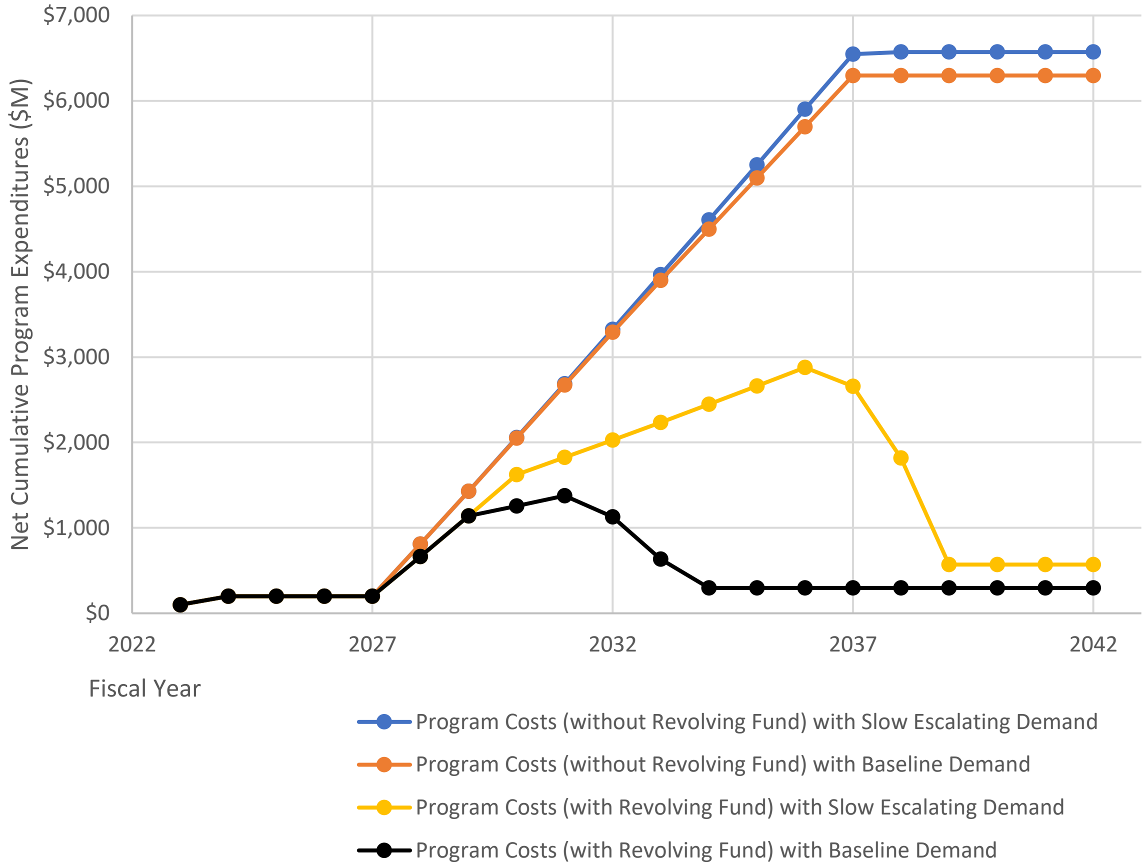

Figure 16. Effect of slowly escalating demand schedule on appropriations requirements with and without a revolving fund for HALEU production at $24M per MTU

The second major insight is that if a commercial HALEU market fails to catalyze (i.e., the no production and demand schedule beyond ARDP case), the resulting change to program operations will have a moderate impact on the total appropriations requirement without the revolving fund and will have a significant impact on both the appropriations requirements with the revolving fund and on the net program costs. The moderate increase in the total appropriations requirement without the revolving ($6.3 billion for baseline case compared with $7.1 billion for no production and demand case in Table 11) is due to the rapid accumulation of costs related to storage of large inventories of purchased HALEU (up to 190 MTU in the no production and demand schedule case) that can only be sold at a limited rate (e.g., 6 MTU / year to satisfy ARDP related needs). The significant increase in the total appropriations requirement with the revolving fund ($1.7 billion compared with $6.4 billion) is due to the need for additional appropriations to make HALEU purchases since only minimal revenue from HALEU sales can be used to support subsequent HALEU purchases. This insight is also true for the increased HALEU production cost summarized in Table 12. Figure 17 illustrates the impact of no commercial production or demand on the total appropriations requirement with and without the revolving fund.

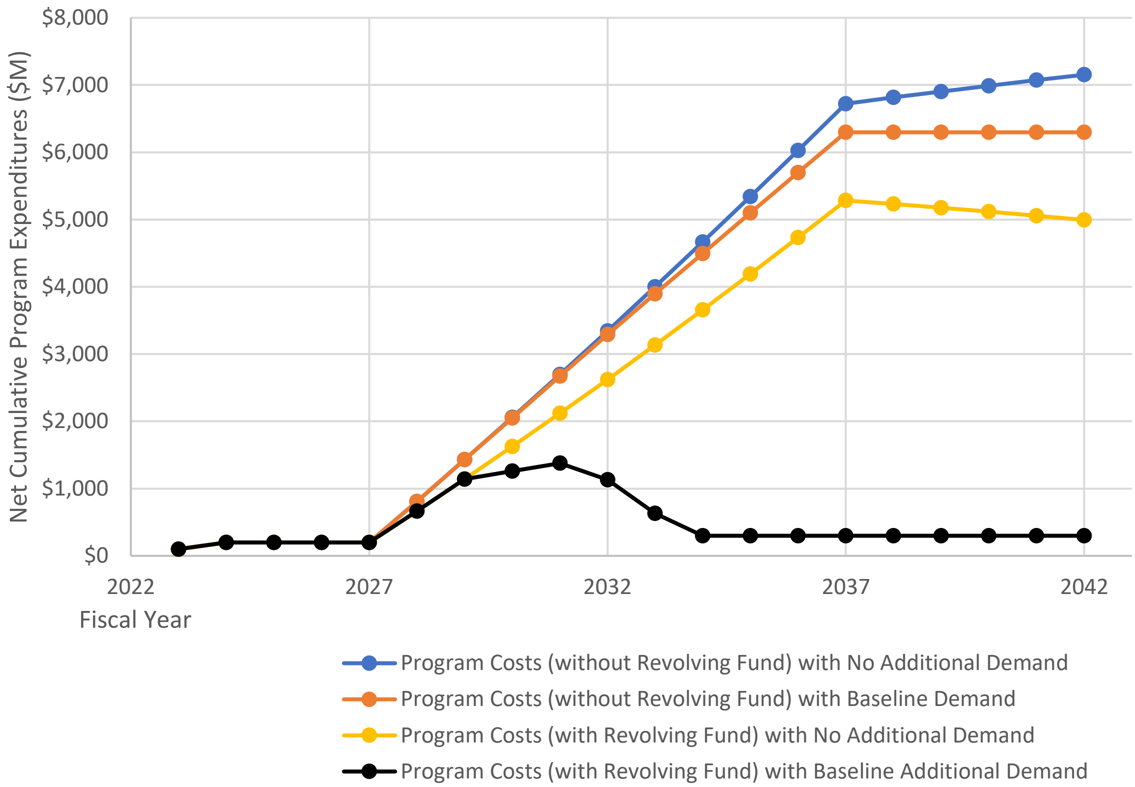

Figure 17. Effect of no HALEU demand or production schedule on appropriations requirements with and without a revolving fund for HALEU production at $24M per MTU

If a commercial HALEU market demand does not develop by the mid-2030s, the HALEU material off-take agreement program is placed in a challenging operational position. The program would purchase large quantities of HALEU (250 MTU) but would only be able to sell small quantities (6 MTU per year for ARDP related needs). This results in a significant HALEU inventory (160 MTU in 2042) that incurs annual storage and handling costs and would require on-going appropriations to support. If a revolving fund is utilized to support program operations, the appropriations requirement would peak in 2037 following completion of the HALEU off-take agreements with suppliers. While the remaining HALEU inventory would be slowly sold over time for ARDP-related needs or could be resold to another federal entity (e.g., DoD for certain defense applications[75] or NASA for space power applications), it would represent a significant financial liability for the program with a value of $3.84 billion in 2042 based on the purchase price of $24M per MTU. This conclusion is consistent for all HALEU production prices although the magnitude of the appropriations cost difference and liabilities will increase with the HALEU production price.

The third major insight is that negotiated contract buy-outs can significantly mitigate increases in the total appropriations requirements and HALEU inventory liabilities associated with the no production and demand schedules beyond ARDP as compared with the baseline production and demand schedules. The evaluated negotiated contract buy-out effectively converts the second five years of HALEU purchases to

[75] HALEU used certain DoD applications may be subject to production restrictions. This “unobligated uranium” for specific defense applications must be produced using U.S.-origin enrichment technology and U.S. origin uranium.

annual payments to the producers set at 40% of the guaranteed HALEU purchase cost (included in operating costs) based on the set HALEU price ($24M/MTU or $30M/MTU) and quantity (total 25 MTU/y). Note that the buy-costs are characterized as "operating costs" in the material off-take agreement analysis.

Figure 18 illustrates the changing balance of operating costs, HALEU purchases, and HALEU sales in a limited production and demand schedules case with a negotiated buy-out and the resulting impact on the program costs with and without a revolving fund.

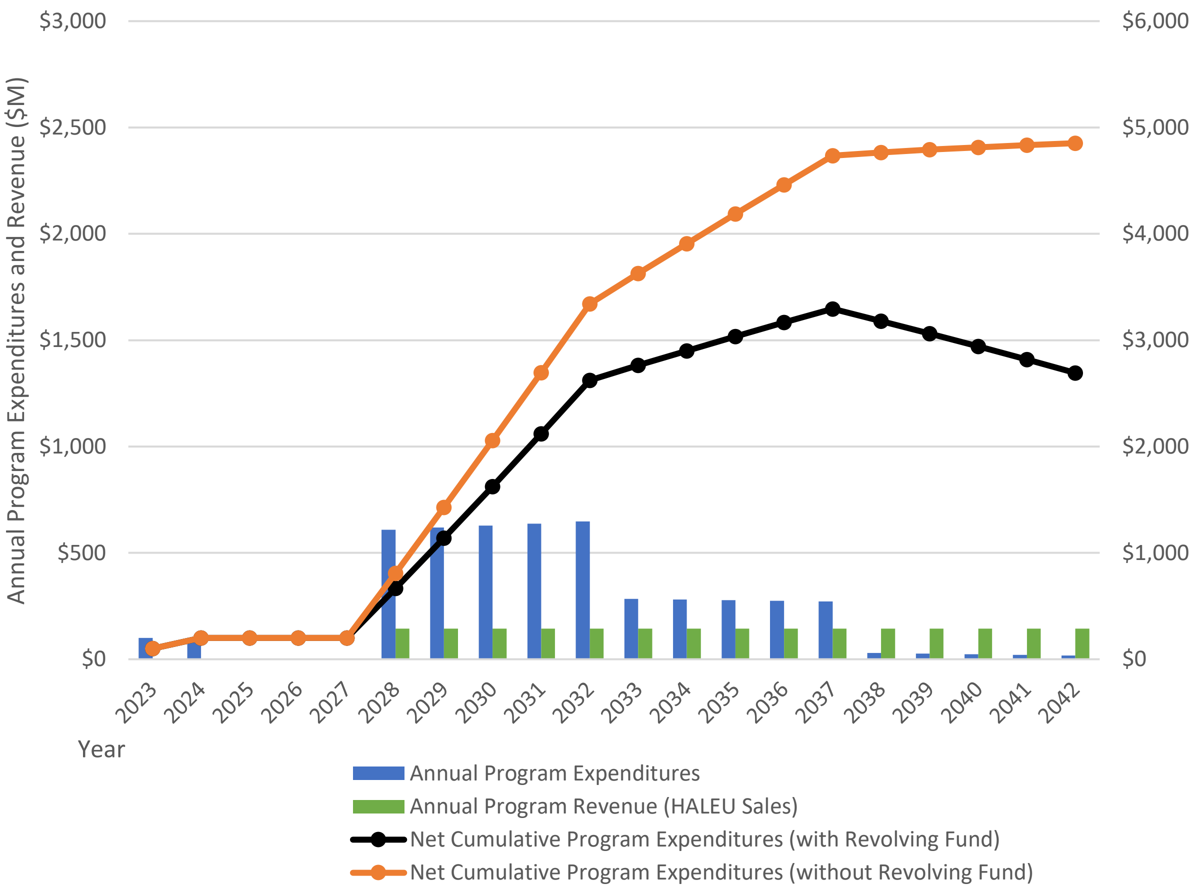

Figure 18. Effect of negotiated contract buy-out on a limited HALEU demand or production schedule on appropriations requirements with and without a revolving fund for HALEU production at $24M per MTU

The negotiated contract buy-out helps mitigate both the total program costs and on-going liabilities if a commercial HALEU market demand does not develop by the mid-2030s. The buy-out reduces the total purchased quantities of HALEU (125 MTU compared with 250 MTU), resulting in a reduced total program cost without the revolving fund ($4.9 billion compared with $7.1 billion in Table 11), reduced total appropriations requirements with the revolving fund ($3.3 billion compared with $5.3 billion), and a reduced on-going HALEU inventory (35 MTU compared with 160 MTU in 2042) that incurs annual storage and handling costs. The on-going storage costs would require on-going appropriations, but if a revolving fund is utilized to support program operations, the appropriations requirement would peak in 2037 as on-going sales of HALEU at low levels are sufficient to offset the storage costs. The remaining HALEU inventory could continue to be slowly sold over time for ARDP-related needs or could be resold to another federal entity such as DOD or NASA, but the financial liability for the program associated with the smaller

HALEU inventory is reduced ($840 million compared with $3.8 billion in 2042 based on the purchase price of $24M per MTU). This conclusion is consistent for all HALEU production prices although the magnitude of the appropriations cost difference and liabilities will increase with the HALEU production price (e.g., costs for HALEU produced at $30M per MTU in Table 12).

The main downside of the negotiated contract buy-out is that while it reduces the total program expenditures, total appropriations requirements, and financial liabilities associated with an unsold HALEU inventory, it results in a larger unrecoverable payment by taxpayers that cannot be recovered by sale of material. The cumulative buy-out payments to producers in the $24M/MTU cost analysis result in additional $1.2 billion in unrecoverable program costs that are ultimately borne by taxpayers.[76] The negotiated contract buy-out mitigates long-term programmatic and financial risk. It is costly, but far less costly than buying hundreds of MTUs of HALEU that can't be sold. Ultimately, the use of the negotiated contract buy-out would be evaluated by DOE and program managers based on their best estimates of both near-term expectations for commercial HALEU demand, opportunities for HALEU sale to other federal entities, and congressional direction to either build and maintain a HALEU stockpile for national security or energy security reasons or to reduce taxpayer burden by ending the program early. This negotiated contract method, however, provides a powerful option to reduce the total program costs and appropriations requirements for the HALEU material off-take agreement and protect the taxpayer from unnecessary expenses if commercial HALEU production and demand do not develop as expected in the 2020s and 2030s. This conclusion is consistent for all HALEU production prices, although the magnitude of the appropriations cost difference will increase with the HALEU production price.

The sensitivity analysis performed by varying production and demand schedules for the HALEU material off-take agreement highlights that program costs will increase if commercial HALEU markets do not develop as expected in the 2020s and 2030s. These effects of program operation, however, be mitigated by the providing a larger initial revolving fund for HALEU production in the case of reduced or delayed demand, and the use of negotiated contract buy-outs in cases where commercial private HALEU demand does not develop in the 2030s. These mechanisms enable the development and operation of a more robust HALEU material off-take agreement that can successfully operate in a range of different market and cost conditions.

4.1.4.4 Baseline Program Cost Sensitivity Analysis with Varying Sale Price Discounts

A sensitivity analysis on the baseline cost analysis is performed to evaluate the impact of varying sale prices below the purchase price on the total program operating costs and appropriations requirements The sensitivity analysis is performed based on the following input conditions:

- baseline production schedule,
- baseline demand schedule,
- HALEU purchase price of $20 million per MTU,
- HALEU sale price varying between 100% and 60% of the purchase price

The baseline cost sensitivity analysis for HALEU material off-take agreements is conducted both with and without the use of a revolving fund to reduce program operational and appropriations requirements. Table 13 summarizes the program operating costs and appropriation requirements for this sensitivity

[76] Additional $1.2 billion in unrecoverable costs is based on 40% payment on 5 years of HALEU purchases of 25 MTU per year at a price of $24 million per MTU for HALEU.

analysis. Figure 19 shows the total appropriations requirements for each HALEU sale price with and without the use of a revolving fund.

Table 13. HALEU sale price cost sensitivity analysis for total appropriations requirements with and without use of a revolving fund

HALEU Purchase Price ($M/MTU)	HALEU Sale Price (% of Purchase)	Net Program Costs ($M)	Total Appropriations Requirement without Revolving Fund ($M)	Total Appropriations Requirement with Revolving Fund ($M)
$ 20.0	100	($297)	$ 6,297	$ 1,377
$ 20.0	80	($1,497)	$ 6,297	$ 1,635
$ 20.0	60	($2,697)	$ 6,297	$ 2,697

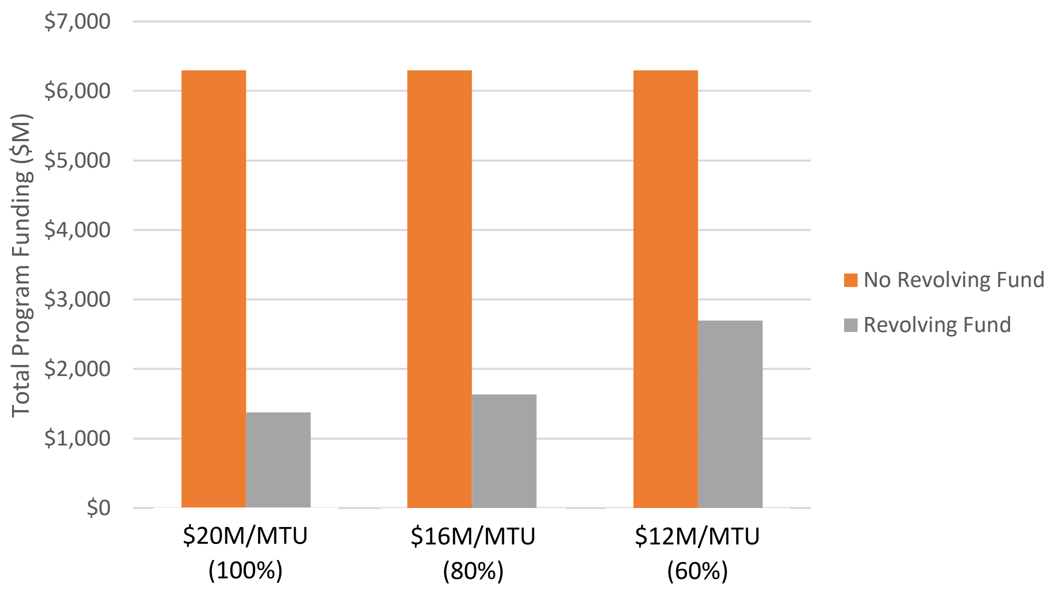

Figure 19. Total appropriation requirements for baseline program cost analysis with and without use of a revolving fund for different HALEU sale prices

The sensitivity analysis on the sale price discounts for the HALEU material off-take agreement provides three important insights into the operation of the HALEU material off-take agreement. First, the total appropriations requirements are the same regardless of sale cost if a revolving fund is not used (Figure *19*). The total program expenditures are based on the total HALEU purchase quantity and HALEU purchase price and do not depend on the HALEU sale prices.

Second, sale of HALEU at price discounts increases the net program costs because the lost revenue associated with sale at a loss (i.e., sale price below purchase prices) cannot be recovered by the program (Table 13). These net program expenditures grow as the sale discount increases. The financial loss for the taxpayer will occur with or without a revolving fund.

Third, the total appropriations requirements when using a revolving fund increase as the sale discount increases. Additional appropriations are required to make up for the lost revenue associated with sales below the purchase price and each discount must be balanced financially by additional appropriations.

The appropriation requirement increases associated with sale at a loss are modest relative to the reduction in total appropriation requirements associated with use a revolving fund, still resulting in a reduction of the appropriations requirements for the HALEU material off-take agreement by approximately 55% to 75% depending on the specific HALEU production cost. The appropriation requirement increases required if HALEU is sold at a loss should be understood when developing estimates for total program appropriation requirements.

4.1.5 Conclusions of HALEU Material Off-take Agreement Cost Evaluations

The HALEU material off-take agreement cost assessments summarized above and detailed in Appendix H provide important insights on the operational constraints, total program costs, and total appropriations requirements associated with a HALEU material off-take agreement under different market conditions. Figure 20 illustrates several key takeaways from the HALEU Material Off-take Agreement cost evaluations.

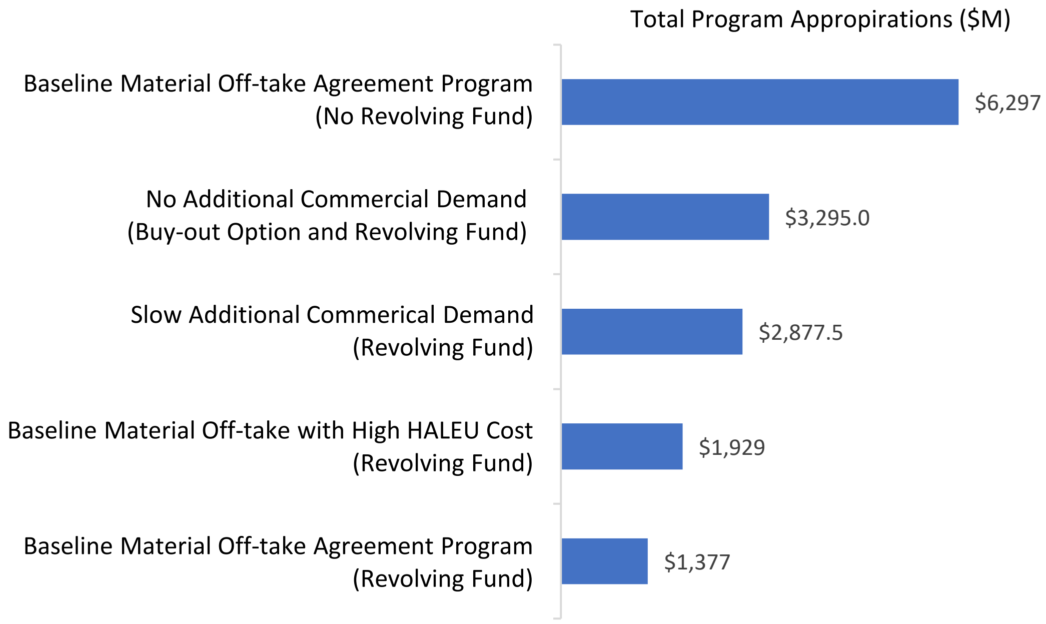

Figure 20. HALEU Material Off-take Agreement Appropriation Requirements ($M) for Different Program Conditions

The first insight from the evaluations is that using a revolving fund for program operation is extremely effective at reducing the total appropriations requirements compared to the total program costs (Figure *14* and Figure 15). Under baseline production and demand scenarios, using a revolving fund can reduce the total appropriations requirements by 75% - 80% and can still reduce the total appropriations requirements by 25% - 55% under slow escalating or no production and demand scenarios. While these reductions do not translate into direct savings to the taxpayer (total unrecoverable program expenditures are the same with or without the revolving fund), the reduced up-front appropriations burden can significantly reduce challenges associated with securing the appropriations necessary to support program activities. Depending how they are managed, revolving funds have the potential to enable economic efficiencies and that are not evaluated here.

The second insight is that an option for a negotiated contract buy-out can significantly reduce the appropriations requirements and financial liabilities associated large HALEU inventories that may result from a HALEU material off-take agreement subject to significant market demand uncertainties (Figure *18*). Use of a negotiated contract buy-out will not result in total program costs or appropriations requirements lower than the baseline production and demand scenario but effectively limits program costs and financial liabilities under worst case HALEU market conditions. However, it is important to note that use of a revolving fund to reduce appropriation requirements also necessitates use of buyout option (Section 4.1.3). Without a buyout option, the appropriations would be too low to guarantee contractual obligations and any off-take contract would becomes subject to the same uncertainty facing existing markets: that commercial sales of HALEU cannot support new investment.

The third insight from the cost assessments is that changes to the HALEU production costs will have the most significant impact on total program expenditures (Figure 15) while changes to the HALEU demand schedule will have the most significant impact on the total appropriations requirements using a revolving fund (Figure 16 and Figure 17). Using a revolving fund is recommended to reduce total appropriations requirements, so it is important to include uncertainties of both the demand schedule and production costs when estimating the total appropriations needs for a HALEU material off-take agreement. While use of conservative bounding assumptions on production cost, demand schedule, and sale price could be used to develop an upper bound estimate for a HALEU material off-take agreement appropriation requirement, this estimate would likely be excessively conservative. Thus, it is important to exercise judgement based on the best estimates and reasonable uncertainty for key inputs (including the production costs and demand schedule) to estimate the total appropriations requirements for a HALEU material off-take agreement.

These three insights and the cost sensitivity analyses summarized above enable estimation of an appropriation requirement for a HALEU material off-take agreement. Table 14 summarizes the total cost and appropriation requirements estimates developed as part of the cost sensitivity evaluations described above. The full complete calculations for the cases summarized in Table 14 are provided in Appendix G.

Without use of a revolving fund or negotiated contract buy-out option, total up-front appropriations of $6.3 billion to $7.2 billion would be needed to support a HALEU material off-take agreement under a variety of demand and production conditions and HALEU production costs of $24,000 / kgU or less.[77] Use of a negotiated contract buy-out option could the reduce total up-front appropriations requirement to $4.8 billion to $5.9 billion without a revolving fund.[78] If HALEU prices increase over to $24,000 / kgU due to various cost driver increases (Sections 2.3.3 and 2.3.4), the total up-front appropriations requirements for a HALEU material off-take agreement without a revolving fund will increase significantly.[79]

With the use of a revolving fund and negotiated contract buy-out option, total up-front appropriations of $1.4 billion to $2.9 billion would be needed to support a HALEU material off-take agreement under a variety of demand and production conditions and HALEU production costs of $24,000 / kgU or less.[80] If additional commercial HALEU demand does not develop, the requirements for a HALEU material off-

[77] Appropriations bounds "Total Required Appropriations with No Revolving Fund" in Cases 1, 2, 3, 6, 7, 12, and 13.
[78] Comparing "Total Required Appropriations with No Revolving Fund" in Cases 7 and 8 and Cases 10 and 11 illustrates the impact of negotiated contract buy-out on appropriation requirements.
[79] "Total Required Appropriations with No Revolving Fund" in Cases 4 and 5 show an increase in appropriation requirements of approximately of $250 million per $1,000 / kgU increase in HALEU price and requirements in Cases 9, 10, and 11 for slow or no additional commercial demand at $30,000 / kgU are significantly higher.
[80] Appropriations bounds "Total Required Appropriations with Revolving Fund" in Cases 1, 2, 3, 6, 12, and 13.

take agreement with a revolving fund and negotiated contract buy-out would increase to $3.3 billion.[81] If HALEU prices increase to over $24,000 / kgU due to various cost driver increases (Sections 2.3.3 and 2.3.4) with baseline HALEU demand, the increase in total up-front appropriations requirements for a HALEU material off-take agreement with a revolving fund are relatively small.[82] However, if HALEU prices increase to over $24,000 / kgU with slow or no additional commercial demand for HALEU, the total up-front appropriations requirements a HALEU material off-take agreement with a revolving fund will increase significantly – up to $4 billion for HALEU prices of $30,000 / kgU.[83]

A total appropriation of $6.3 billion to $7.2 billion for the HALEU material off-take agreement would enable successful operation of the program under a wide variety of market scenarios and help catalyze a domestic commercial HALEU market. Lower total appropriations of $1.5 billion to $2.9 billion for the HALEU material off-take agreement with a revolving fund could enable program operation but may require additional appropriations if market conditions diverge significantly from the baseline costs or schedules.[84]

The methodology and assumptions described in this paper can be repeated for different market assumptions to provide insights on the total cost and appropriation requirements associated with specific demand, production, or cost conditions.

[81] "Total Required Appropriations with Revolving Fund" in Case 8 is $3.3 billion. The use of a negotiated contract buy-out option enables Case 8 appropriation requirements to bound Case 7.

[82] "Total Required Appropriations with Revolving Fund" in Cases 4 and 5 are less than $2 billion.

[83] "Total Required Appropriations with Revolving Fund" in Cases 9 and 11 are less than $4 billon. The use of a negotiated contract buy-out option enables Case 11 appropriation requirements to bound Case 10.

[84] The HALEU material off-take agreement program appropriations requirements are consistent with the HALEU portion of the combined LEU-HALEU program appropriations using a revolving fund described in NIA's June 2023 paper "Additional Flexible Funding is Needed to Break Dependence on Russian Nuclear Fuel".

Table 14. Summary of HALEU Material Off-take Agreement Cost Sensitivity Analyses

Sensitivity Analysis Case	Production Schedule	HALEU Purchase Price ($M/MTU)	Demand Schedule	HALEU Sale Price (% of Purchase)	Negotiated Contract Buy-out Used?	Total Required Appropriations with No Revolving Fund ($M)	Total Required Appropriations with Revolving Fund (Note 1) ($M)
Case 1	Baseline	$ 16	Baseline	100%	No	$4,297	$1,009
Case 2	Baseline	$ 20	Baseline	100%	No	$5,297	$1,193
Case 3	Baseline	$ 24	Baseline	100%	No	$6,297	$1,377
Case 4	Baseline	$ 30	Baseline	100%	No	$7,797	$1,653
Case 5	Baseline	$ 36	Baseline	100%	No	$9,297	$1,929
Case 6	Slow Escalating	$ 24	Slow Escalating	100%	No	$6,572	$2,878
Case 7	No Production	$ 24	No Demand	100%	No	$7,153	$5,283 (Note 2)
Case 8	No Production	$ 24	No Demand	100%	Yes	$4,853	$3,295
Case 9	Slow Escalating	$ 30	Slow Escalating	100%	No	$8,072	$3,472
Case 10	No Production	$ 30	No Demand	100%	No	$8,653	$6,423 (Note 3)
Case 11	No Production	$ 30	No Demand	100%	Yes	$5,903	$3,985
Case 12	Baseline	$ 24	Baseline	80%	No	$6,297	$1,636
Case 13	Baseline	$ 24	Baseline	60%	No	$6,297	$2,697

Note 1) Use of a revolving fund as part of a HALEU Material Off-take Agreement program to reduce appropriation requirements requires the availability of buyout options to secure private capital investments and guarantee capital recovery on new production facilities.
Note 2) Case 7 Total Required Appropriations with Revolving Fund is bounded by Case 8 Total Required Appropriations with Revolving Fund if a negotiated contract buy-out is used to limit program operational costs and liabilities.
Note 3) Case 10 Total Required Appropriations with Revolving Fund is bounded by Case 11 Total Required Appropriations with Revolving Fund if a negotiated contract buy-out is used to limit program operational costs and liabilities.

4.2 HALEU Production Services Agreements

The main challenge for the HALEU material off-take agreement is that purchasing the quantities of HALEU necessary to catalyze private investment in new HALEU production capacity requires significant program expenditures and the funding requirements are highly dependent on LEU commodity prices (natural uranium, conversion, and LEU enrichment). The HALEU Production Cost Model illustrates how LEU fuel cycle services may represent up to 65% of total HALEU production costs (see sections 2.3.1 and 2.3.2).

The HALEU "production services agreement" program enables the federal government to focus on HALEU-specific production gaps by making guaranteed contracts for HALEU enrichment and deconversion as a service to create a reliable demand signal for commercial investment in new production facilities. A HALEU production services agreement is analyzed below to quantify the total funding requirements for such a program with sensitivity analyses to evaluate the impact of varying purchase quantity, pricing, and duration on program operation requirements.

This section provides descriptions and detailed analysis of a HALEU production services agreement. The major subsections include:

- Description of a HALEU production services agreement and factors that affect program operation and costs (Section 4.2.1)
- Evaluation of HALEU production services agreement costs under different operational and market conditions (Section 4.2.2)
- Summary of HALEU production service agreement costs and policy recommendations (Section 4.2.3)

4.2.1 HALEU Production Services Agreement Description

The HALEU production services agreement model allows the federal government to make long-term contracts with HALEU fuel cycle companies to incentivize investment in new production capability. For example, the government could contract with enrichment companies for a certain amount of annual separative work (SWU/y) at a fixed price ($/SWU) or a certain amount of deconversion services (MTU/y) at a fixed price ($/MTU). If there is demand for the enrichment or deconversion services in a particular year, the federal government would transfer or resell the enrichment service contracts to advanced reactor developers, fuel fabricators, reactor owners, or other fuel buyers at cost. The federal government would also have the option to pay for the uranium feed necessary for HALEU production (LEU-enriched UF_6) to produce HALEU owned by the federal government for later use or resale to commercial customers. If there is no commercial or federal demand for the contracted HALEU production services, the HALEU fuel cycle company would retain the contract value for that period as a fixed payment and would be commercially free to use the production capacity for other customers.

Figure 21 illustrates the HALEU production services agreement program model and the different possible program outcomes.

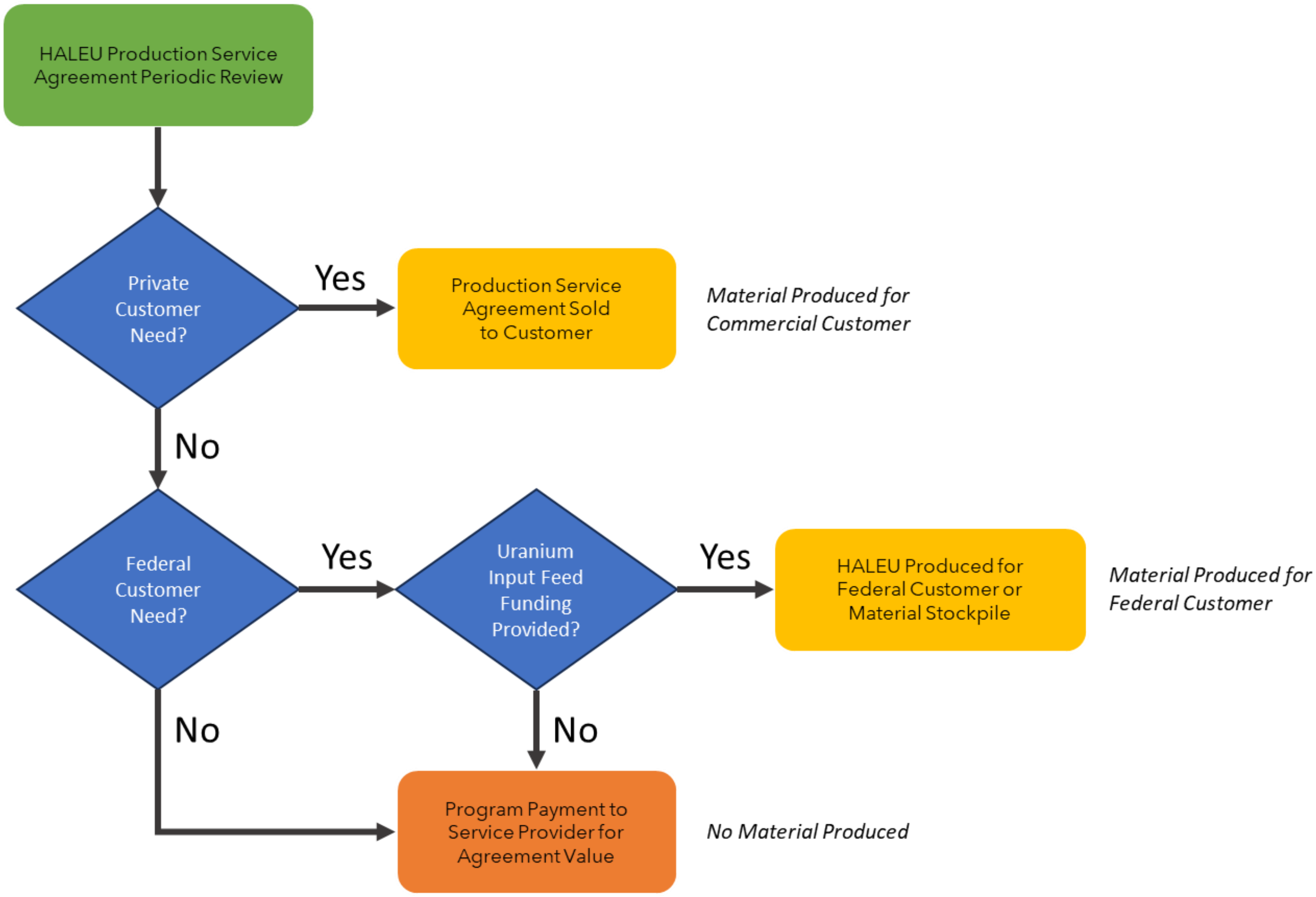

Figure 21. HALEU Production Services Agreement

The HALEU production services agreement program is designed to focus programmatic federal support on HALEU production services (specifically enrichment, deconversion, and transportation) that would otherwise not receive sufficient commercial demand signals to incentivize private investment to support development of a robust domestic HALEU fuel cycle. The HALEU material off-take agreement model (Section 4.1) creates a federally guaranteed market for HALEU material that will catalyze commercial private investment in new HALEU production. The HALEU material off-take program has the twin benefits of providing fuel demand assurance (incentivizing private investment in HALEU production capacity) and providing fuel supply assurance (enabling private investment in advanced reactor projects that will require HALEU). The HALEU material off-take program, however, requires significant forward appropriations to provide guaranteed purchase contracts at the quantities, prices, and durations necessary to support private infrastructure investments. While use of a program revolving fund coupled with a contract buyout provision can help defray the costs associated with HALEU production, it still requires significant upfront appropriations ($1 billion - $4 billion) to ensure program operation.[85]

Review of the HALEU production cost model provides insights on different cost drivers for HALEU production, magnitude of each cost driver, sensitivity of these drivers to cost variation, and existing commercial activities related to each cost driver (see section 2.3). In the baseline HALEU production, the major cost drivers are costs associated with LEU production (C_{input},

[85] Appropriations requirements for the HALEU material off-take agreement are presented in Table 14.

$C_{convert}$, and $C_{enrich_{LEU}}$) that are required inputs for HALEU production and represent 65% of total HALEU production costs. These cost drivers are significant for two major reasons.

First, variations in these costs are currently subject to market forces for existing reactors and vulnerable to significant price variations based on changing commercial and geopolitical conditions. Determining a fixed price for HALEU production in an off-take program would require the federal government and companies to make projections of varying market conditions for LEU fuel cycle activities over the next 10 to 15 years. The past 15 years of commercial LEU markets have seen significant variations based on commercial and geopolitical events (including the Fukushima nuclear reactor accident, changing national policies on nuclear energy production, and the Russian invasion of Ukraine). There is little reason to believe that LEU markets can be accurately forecast for the next 15 years without a significant margin or fully guaranteed long-term production contracts.

Second, while the LEU cost drivers are important, the amount of LEU required to support the program's near-term HALEU production is small compared with existing commercial demand (e.g., approximately 916 kSWU per year for 25 MTU of HALEU production compared with U.S. LEU enrichment demand of 14,176 kSWU in 2022). Federal procurement of LEU production services (e.g., 916 kSWU of LEU enrichment) for HALEU production would not likely result in the development of new domestic commercial LEU enrichment capacity. The existing commercial LEU market is mature and new capacity investment would be based on market signals for increased long-term future LEU and HALEU demand. Specifically focusing federal funding to support the LEU production as feed for HALEU is not likely required to significantly impact near-term domestic HALEU production. Focusing federal funding on other cost drivers that are less commercially mature maximizes the market impact of federal support.

The remaining major cost drivers in the baseline HALEU production cost model include HALEU enrichment ($C_{enrich_{HALEU}}$), HALEU deconversion ($C_{deconvert}$), and overhead costs associated with HALEU production (C_{admin}) such as transportation and storage. These activities represent 35% of HALEU production costs in the baseline cost model, but these activities are unique in that they do not have existing commercial customers to drive demand and new commercial production capacity. The market demand gap for HALEU production can be reduced by developing commercial markets for the cost drivers of HALEU enrichment, HALEU deconversion, and other HALEU services like transportation and storage. Creating a program to support investment in these specific commercial activities would facilitate development of a commercial HALEU market while requiring significantly less appropriations and reducing program costs sensitivity to LEU fuel cycle market volatility. This approach focuses federal support on the part of the HALEU supply chain that requires novel new facility investment, rather than spending billions of federal dollars buying LEU feed from existing commodity markets.

In a HALEU production services model, the program would provide contracts to commercial companies to provide a specific HALEU production service for a certain production schedule (e.g., duration and quantity of service) at a specific cost. The analysis below quantifies the total funding requirements for such a program and performs sensitivity analyses to evaluate the impact of varying purchase quantity, pricing, and duration on program operation requirements.

4.2.2 HALEU Production Services Agreement Cost Evaluation

Quantifying the costs of a HALEU production services agreement program is simplified by leveraging insights from the HALEU production cost model. The HALEU enrichment, deconversion, and administrative needs and costs associated with HALEU production can be calculated based on the baseline models and assumptions provided in Appendix B and Appendix C. Table 15 summarizes the needs for a enrichment service agreement for each MTU equivalent of production, annual program costs for a 10 MTU and 25 MTU annual program, and total program costs assuming 250 MTU of HALEU production.

Table 15. HALEU Production Services Agreement Program Cost Summary

Cost Category	Quantity per MTU HALEU	Baseline Cost Estimate	Annual Program Costs		Total Program Cost
			10 MTU/y	25 MTU/y	250 MTU
$C_{enrich_{HALEU}}$	5940 SWU	1,000 $/SWU	$59,500,000	$148,750,000	$1,487,500,000
$C_{deconvert}$	1 MTU	2,000,000 $/MTU	$20,000,000	$50,000,000	$500,000,000
C_{admin} (HALEU and other administrative costs)	1 MTU	100,000 $/MTU	$1,000,000	$2,500,000	$25,000,000

Guaranteed contracts for HALEU production services could reduce total program expenditures and program liabilities compared HALEU material off-take agreements because they do not require the federal government to pay for the uranium feed material from existing LEU fuel cycle companies. The costs associated with creating commercial services markets necessary to support an equivalent of 25 MTU year of HALEU production are significantly less than the cost associated with directly procuring 25 MTU year of HALEU. Total contracts to support 250 MTU of HALEU production (including enrichment, deconversion, and administrative costs) could be guaranteed with an appropriation of $2 billion using the baseline cost assumptions. This would reduce the scope of government program, eliminating the need for DOE to continuously engage in HALEU sales to sustain program operation using a revolving fund. The production service costs could increase if higher per SWU or MTU costs are required to incentivize private investment in new production capacity (subject to many of the uncertainties previously discussed), but the appropriation needs and financial risks associated with this program would still be less than those for the HALEU material offtake program. The costs in Table 24 can be scaled based on the HALEU enrichment, deconversion, or overhead costs to estimate appropriations requirements under increased production cost conditions.

In an ideal market scenario, the federal government would be able to transfer or resell the HALEU production contracts (HALEU enrichment, deconversion, and services) to private companies to produce HALEU for commercial applications or use some of it to support government needs such as DOE, DOD, or NASA.[86] If the program is unable to transfer or resell the contracts to commercial or federal customers, the program would be required to either supply the HALEU service provider with uranium feedstock to produce HALEU or pay the service provider the value of the contract without receiving any services. The program (using additional appropriations) could procure uranium (enriched LEU as UF_6) and provide it to the service provider to produce enriched HALEU as UF_6, deconverted HALEU as an oxide or metal, or transported and stored HALEU based on the specific service contract. The government would be able to produce and take possession of HALEU under this program to either support other government customers who need HALEU or stockpile it for future commercial needs.

[86] Applicability of the production service contracts to different federal customers would depend on whether uranium produced by the supplier was considered obligated or unobligated based on the origin of both the uranium feed material and the processing technology.

This program effectively triples the market power of federal appropriations (focusing on cost drivers representing 35% of HALEU production costs) compared to a HALEU material off-take program by enabling DOE to directly catalyze investment in new HALEU production infrastructure that otherwise would not have strong and reliable market signals.

4.2.3 Conclusions of HALEU Production Services Agreement Cost Evaluations

The HALEU production services agreement is a unique method to focus federal incentives and market demand for HALEU enrichment, deconversion, and transportation as a service. This significantly reduces the appropriation requirements associated with a HALEU program as compared with a HALEU off-take agreement program and ensures that federal appropriations are focused on the part of the HALEU supply chain that require strong market signals to secure the capital investment to design, licensing, construct, and operate new HALEU production facilities. A total appropriation of $2 billion for a HALEU production services agreement would enable successful operation of this program and would help catalyze investment in domestic HALEU enrichment facilities.

This program approach can reduce the long-term financial risk for both companies and the federal government. HALEU production companies do not need to hedge against long-term commodity prices if setting fixed prices for HALEU production as part of a material off-take agreement and the federal appropriators do not need to include LEU fuel cycle price volatility when allocating funding to a material off-take agreement that may use an escalating or cost-plus contract structure for HALEU production. This helps decouple HALEU funding from market forces related to the existing LEU fuel cycle and helps the government avoid competition against U.S. utilities in purchasing LEU feed material.

This program, however, comes with some limitations. Investments in these facilities by taxpayers, would not be recovered during program operation if contracts are not successfully transferred to other customers and additional funding is not appropriated to produce HALEU using the contracted services – instead paying the service company the value of the contract. In this way, the program effectively converts to an infrastructure grant if there is no commercial demand or additional federal support for HALEU procurement. If the government can transfer the contracts or if the program exercises the production contract and any material was produced and procured by the program is subsequently sold, the program would be able to recover a significant fraction of the initial appropriations.

Exercising the production option as part of the HALEU production services program would require substantial additional funding (hundreds of millions of dollars per year) to purchase HALEU material from the supported facilities by paying for the needed uranium feed material. Additional production services agreement contracts for any facilities or production activities requiring significant capital investment (including enrichment, deconversion, and transportation) may be required to ensure that these steps in the HALEU production process do not become HALEU production process bottlenecks.

It is also important to note that some changes to the existing legislative language in the Energy Act of 2020 may be necessary to authorize a HALEU production services agreement program. It is not clear if the existing authorizing language for the HAP allows DOE to contract for services for HALEU production or if they are only authorized to procure HALEU material. Solution of any authorization challenges and appropriation challenges are necessary before the successful implementation of the HAP.

The HALEU production services enables the federal government to leverage available program funding and can reduces up-front appropriation requirements and for the operation of the HALEU availability program.

4.3 Summary and Discussion of HALEU Program Evaluations

The HALEU program evaluations provide several important insights on the costs and operational challenges associated with a HALEU material off-take agreement program and a HALEU production services agreement program.

The guaranteed government purchase and sale of HALEU through a material off-take agreement program can be designed to incentivize private investment in new commercial HALEU production. The program can minimize taxpayer burden while supporting new HALEU production capacity, but requires substantial program funding and management to successfully operate based on the range of possible HALEU cost, demand, and supply scenarios.

Total up-front appropriations of $6.3 billion to $7.2 billion for a HALEU material off-take agreement program would enable successful operation of the program under a wide variety of market scenarios to catalyze a domestic commercial HALEU market. Smaller total up-front appropriations of $1.5 billion to $2.9 billion for the HALEU material off-take agreement program could enable program operation but may require additional appropriations if market conditions diverge significantly from the expected HALEU production costs or industry HALEU demand.[87]

The majority of the program funding required for a HALEU material off-take agreement program is spent on procuring LEU feed material from existing LEU fuel cycle markets as opposed to building or operating HALEU enrichment facilities. Approximately 65% of the total HALEU production costs are due to uranium mining, conversion and LEU enrichment costs, so material off-take agreements will directly support purchases from LEU markets. This also makes the appropriation requirements for the HALEU material off-take agreement program sensitive to LEU fuel cycle commodity prices.

Enabling the use of a "revolving fund" (permitting revenue from prior program HALEU sales to directly fund future HALEU purchase) is extremely effective at reducing the total appropriations requirements for a HALEU material off-take agreement program, reducing the total appropriations requirements by 75% - 80% under baseline assumptions. The reduced up-front appropriations burden can significantly reduce challenges associated with securing the appropriations necessary to support program activities. The net program expenditures will be the same whether or not a revolving fund is used, unless the management of the revolving fund itself enables the realization of potential additional economic efficiencies and taxpayer benefits that were not evaluated here.

Enabling an option for a "negotiated contract buy-out" can significantly reduce the appropriations requirements and government financial liabilities associated with large HALEU inventories that may result if commercial demand does not materialize as expected. Use of a negotiated contract buy-out effectively limits program costs and financial liabilities under worst case HALEU market demand conditions and protects taxpayers. This option for a negotiated contract buy-out is required to effectively use a revolving fund to reduce up-front appropriations requirements.

Alternatively, the government can procure HALEU production services (HALEU enrichment, deconversion, and transportation) through HALEU production services agreements. This program can focus government

[87] The HALEU material off-take agreement program appropriations requirements are consistent with the HALEU portion of the combined LEU-HALEU program appropriations using a revolving fund described in NIA's June 2023 paper "Additional Flexible Funding is Needed to Break Dependence on Russian Nuclear Fuel"

support on catalyzing investment in new commercial HALEU production activities that do not currently have reliable supply and demand signals:

Total up-front appropriations of $2 billion for a HALEU production services agreement program would enable successful operation of the program and would help catalyze investment in domestic HALEU production facilities. The program can recover costs over time through the sale or transfer of HALEU enrichment, deconversion, or other production service contracts to private companies or other federal customers. The program would also have the option to produce HALEU for a government stockpile using the production service contracts, but additional future appropriations would be necessary to acquire the required LEU feedstock material from existing LEU commodity markets.

The HALEU production services agreement program reduces the long-term financial risk for both companies and the federal government. HALEU production companies do not need to hedge against long-term commodity prices if setting fixed prices for HALEU production as part of a material off-take agreement. The federal appropriators do not need to account for LEU fuel cycle price volatility when allocating funding to a material off-take agreement that may use an escalating or cost-plus contract structure for HALEU production. These attributes reduce the risk of program failure due to insufficient funds.

The HALEU production services agreement program focuses federal investment towards new HALEU production capacity. The HALEU production service agreements are entirely focused on activities that require new facilities or operations (HALEU enrichment, deconversion, and transportation). The program more effectively supports new production capacity rather than procuring LEU feed material from existing LEU fuel cycle markets. The program also provides guaranteed payment over a multi-year period for new HALEU production services, enabling private companies to secure capital funding critical to design, license, construct, and commission new HALEU production facilities.

New legislative authorization may be required to enable use of service agreements to catalyze HALEU production. The authorizing legislation for the Department of Energy HALEU Availability Program in the Energy Act of 2020 requires the federal government to “acquire and provide” HALEU for commercial advanced reactor companies to help catalyze new domestic HALEU production, but it is not clear whether use of service contracts to catalyze new domestic HALEU production would be permitted. New legislative authorization may be required to allow DOE to use this program structure to support development of new domestic HALEU production capacity.

Both programmatic options to catalyze investment in new commercial HALEU production activities require significant increases in upfront appropriations to support successful operations. The new private capital investments required to design, license, construct, and commission new HALEU production facilities require commercial assurance of return. Upfront appropriations guarantee the availability of program funds and reduce commercial risk associated with reliance on the annual appropriations process.

The programs evaluated in this report can be re-evaluated for different market assumptions to provide insights on the total cost and appropriation requirements for the two program structures and the potential benefits and drawbacks of different approaches to catalyze investment in new commercial, domestic HALEU production.

5 Policy Implications of HALEU Program Evaluations

This report develops quantitative models of HALEU production costs and evaluations of different program models to catalyze private investment in a mature, sustainable, and domestic commercial HALEU fuel cycle. The models and evaluations provide both methodologies and quantitative results that yield insights on the cost drivers associated with HALEU production and programmatic factors that can be used to control or reduce the costs associated with ensuring domestic HALEU availability and catalyzing private investment in long-term HALEU production capacity. There are several key policy implications that are supported by the quantitative and qualitative evaluations performed in this report. The implementation of these policy recommendations can help decrease the time and cost associated with catalyzing development of a mature commercial HALEU market in the United States, increase the likelihood that the program will support development of a sustainable industry that does not require continued federal support, and enable increased investment in the development and deployment of advanced reactors in the United States by providing a pathway to reliable and cost-competitive domestic HALEU production.

1. Federal funding must be guaranteed over a substantial period of time (10 years) to catalyze private capital investment in a sustainable domestic commercial HALEU market.

The HALEU production cost model highlights that investments in new HALEU enrichment or deconversion infrastructure will not be supported by existing markets because cost escalation related to limited market supply could significantly increase HALEU production costs. The HALEU program evaluations demonstrate that guaranteed market demand at sufficient volume and pricing over a period of 10 years is required to create the market conditions necessary for private investment in new HALEU production infrastructure. If funding is not guaranteed or sustained over a sufficient period of time, it is unlikely that market conditions will support substantial private investment in HALEU production.

2. Significant increases in total federal funding are necessary to catalyze private investment in commercial HALEU production.

The HALEU program evaluations show that catalyzing a domestic HALEU market using a material off-take agreement will require significantly greater appropriations $6.3 billion to $7.2 billion) compared to the funding currently available through the IRA ($500 million).[88] Use of a HALEU material off-take agreement will directly address issues related to both HALEU supply and demand uncertainty but will require substantially more up-front appropriations to adequately support operation and ensure successful program outcomes. Use of programmatic options such a revolving fund and buy-out option can reduce the total appropriations requirements, but federal funding beyond the $500 million in the IRA is needed.

Use of a HALEU production services agreement can address issues related to HALEU enrichment demand signals without the need for the federal government to directly purchase and resell HALEU. The program decouples HALEU production support from LEU fuel cycle commodity markets and enables the more predictable support of new HALEU production infrastructure (including HALEU enrichment, deconversion, and transportation). This programmatic change can reduce appropriation requirements under most conditions and reduce programmatic risk for companies and the federal government. A HALEU production

[88] The HALEU material off-take agreement program appropriations requirements are consistent with the HALEU portion of the combined LEU-HALEU program appropriations using a revolving fund described in NIA's June 2023 paper "Additional Flexible Funding is Needed to Break Dependence on Russian Nuclear Fuel"

services agreement program would require approximately $2 billion in up-front appropriations to ensure program operation.

The federal government would retain the option to produce HALEU using the HALEU production services agreement if enrichment, deconversion, or other supported contracts were not transferred to private companies. Exercising these production options would require additional funding of approximately $250 million to $300 million per year for 10 years would be required to acquire the converted and enriched LEU feedstock required as inputs for 25 MTU per year of HALEU production (depending on LEU commodity costs). This material (supplied by LEU fuel cycle facilities) could then be directly sold to commercial customers, stockpiled for future commercial use, or transferred or sold to other government customers. This production is optional; private investment in HALEU services are protected by the guaranteed HALEU production service contracts and the taxpayer is protected against volatility in LEU market prices. These conditions can incentivize both public and private support for new HALEU production infrastructure.

For both analyzed HALEU programs, significant increases in total appropriations are needed to help catalyze HALEU market development and maturation.

3. New HALEU program authorizations are needed to most efficiently support HALEU market development and maturation.

The HALEU program evaluations highlight the role of two different operating characteristics in catalyzing market development and minimizing appropriations requirements for a HALEU program:

- use of a revolving fund and negotiated contract buy-outs to support a HALEU material off-take agreement using fewer up-front appropriations and limit taxpayer liabilities. These specifically help reduce the taxpayer risks related to significant supply and demand uncertainties and total up-front appropriations requirements. Additional economic efficiencies and taxpayer benefits are also possible through effective revolving fund management. New legislative authorization (such as new authorizations included in the introduced *Nuclear Fuel Security Act*[89]) is likely required to enable use of a revolving fund to support a HALEU material off-take agreement.
- use of a production services agreement model for HALEU enrichment, deconversion, and other overhead services to catalyze market development of new production infrastructure without market demand and reduce total up-front appropriations requirements. New legislative authorization is required to enable use of service agreements to catalyze HALEU production.

Authorizing these changes to program operation through legislative changes to the HALEU Availability Program would increase the likelihood of program success and reduce the total up-front appropriations requirements, thus enabling the faster development and implementation of a sustainable and successful HALEU development program.

[89] H.R.1086: Nuclear Fuel Security Act

6 Conclusion

This report characterizes and quantifies HALEU production costs and analyzes two different types of HALEU availability programs – a HALEU “material off-take” program and a HALEU “production services” program. The cost models and program analyses developed and presented in this report provide a common basis for discussion between advanced reactor companies, fuel cycle service providers, fuel end users, and policymakers on the programmatic and funding needs to catalyze domestic commercial production of HALEU.

Characterizing the cost drivers and quantifying the costs for HALEU production using a repeatable methodology enable better estimation and discussion of HALEU production costs as additional information and estimation of cost drivers become available. The modeling of two federal programs that support HALEU availability provides policymakers the tools to evaluate HALEU production proposals and determine which options can most effectively and efficiently be used to catalyze private investment in new HALEU production infrastructure. These results also underscore the challenges associated with commercial HALEU production and the need for continued federal support to ensure a robust, reliable, and domestic commercial supply chain for HALEU.

The HALEU production cost model and evaluations of HALEU availability programs are not intended to provide definitive quantification of the costs associated with HALEU. Instead, the methods described in this report are intended as a transparent basis for discussions between advanced reactor companies, fuel cycle service providers, fuel end users, and policymakers on the needs to catalyze domestic commercial production of HALEU.

Solving the “chicken-and-the-egg” problem associated with misaligned HALEU market supply and demand signals can be accomplished using federal government support. Clear understanding of private commercial requirements, public funding constraints, and operational uncertainty is critical to creating a robust program that catalyzes private investment in the HALEU fuel cycle and leads to a sustainable domestic market for HALEU.

The successful commercialization of advanced nuclear reactors will require a stable and cost-competitive HALEU market that can provide the fuel needed for these reactors to generate safe, clean, and reliable energy.

Appendix A – Alternative HALEU Production Pathways

Near-term HALEU availability is a major concern for advanced reactor developers and customers due to the time required to design, licensing, construct, and commission new HALEU enrichment and deconversion facilities. The fuel fabrication process is expected to take two or more years based on LWR fuel production schedules, so advanced reactors planning operation in the late 2020s may require enriched uranium delivery to advanced reactor fuel fabricators as early as 2026. Uranium enrichment companies estimate that construction of new HALEU production capacity may take 3 – 7 years depending on existing enrichment site licenses and supply chains. There is likely some near-term HALEU demand that cannot be satisfied by new HALEU production capacity.

Near-term HALEU production pathways that do not require new HALEU enrichment or deconversion infrastructure have been proposed by industry and government to meet near-term HALEU demand. These production pathways are "stopgap" solutions that do not result in new commercial production infrastructure but are intended to meet near-term need by using previously enriched uranium. These pathways include the recovery of HALEU from prior DOE fuel programs and downblending of excess high-enriched uranium (HEU) from DOE stockpiles that could be used to help meet commercial HALEU demand. Uranium downblending is the process of diluting higher enriched uranium with lower enriched uranium to create an intermediate enriched product. Downblending in the context of HALEU production refers to diluting HEU (e.g., >20% U-235) with natural uranium (0.711% U-235) or depleted uranium (<0.711% U-235) to produce HALEU (<19.75% U-235) or LEU (<5% U-235) without the need for additional uranium enrichment.

One near-term pathway is the recovery of HALEU from prior previous DOE fuel programs and downblending of excess high-enriched uranium (HEU) from DOE stockpiles that could be used to help meet commercial HALEU demand. Several historical DOE fuel programs used HEU or HALEU fuel for reactor experiments in the 1960s – 1990s and some of these fuel elements could be processed, downblended (if necessary), and reused to fuel certain advanced reactors. For example, around 10 MTU of HALEU will be recovered from the Experimental Breeder Reactor II (EBR-II) at Idaho National Laboratory (INL). It should be noted however, that recovered fuel from these sources can have isotopic compositions that make it challenging to use such fuel in a commercial advanced nuclear reactor for power production.

Another near-term pathway is the downblending of existing stocks of HEU within the national laboratory complex (typically from U.S. defense programs) that could, in principle, be used for HALEU production through uranium downblending. HALEU produced from the downblending of DOE HEU stockpiled material would have few isotopic impurities and be easily integrated into HALEU fuel fabrication processes for commercial advanced reactors. While HEU downblending may be useful to meet near-term HALEU demand before commercial-scale HALEU production comes online, it is a stopgap solution that faces several programmatic and operational constraints.

First, the available quantities of HEU for downblending are limited. Producing HALEU using uranium downblending would require access to and use of the stockpiled HEU within the DOE National Nuclear Security Administration (NNSA). This approach holds the potential to yield roughly 4-8 MTU of HALEU per year for each MTU of HEU downblended.[90] Downblending HEU with LEU (<5% U-235) instead of natural

[90] NIA | Catalyzing a Domestic Commercial Market for HALEU

uranium or depleted uranium to produce HALEU could help increase the amount of HALEU produced for each MTU of HEU downblended (approximately 25% more production per MTU).

The U.S. halted HEU production in 1992, so the existing stockpile of HEU is a finite resource unless the federal government restarts HEU production.[91] The quantities of surplus HEU are relatively small; in 2016 the Obama administration announced that only 41.6 MTU of HEU was considered "surplus" availability for potential downblending.[92] Use of downblending to support near-term HALEU needs could require use of a non-trivial percentage of the stockpile. The NNSA, therefore, will exercise caution when it comes to reducing their HEU stockpiles, even after accounting for material that has already been committed to other federal energy and defense programs. This conservatism provide NNSA additional margin for delays in any future restarted HEU production activities.

Second, downblending requires specialized process facilities and is an expensive and time-consuming process. A recent contract award by NNSA to downblend "scrap" HEU material will cost $116.5 million and produce "over two metric tons" of HALEU.[93] This implies a cost of more than $50,000 per kgU for downblending alone. While the process is expected to produce "several hundred kilograms" as early as 2024, it will take five years to produce the contracted 2 MTU of HALEU. The cost and schedule of this program is driven by BWXT's need to expand existing downblending production facilities and capacity to meet the increased demand. Developing sufficient downblending production capacity to produce 5 – 10 MTU per year of HALEU may require similar infrastructure investments and deployment schedules as new HALEU enrichment capacity. While leveraging existing downblending production capacity enables near-term production of limited quantities of HALEU, it is not clear whether downblending could effectively and efficiently scale to satisfy all near-term HALEU needs.

Third, the available HEU stockpiles from downblending are inherently finite. Downblending represents, at best, a stopgap solution to HALEU production. A utility will not make a 30- or 60-year commitment to a new advanced reactor requiring HALEU fuel unless they have confidence that fuel will be commercially available for the lifetime of the reactor. To the extent that an HEU downblending program might meet some of the near-term, high-fidelity demand, there is a risk that it could delay or displace private sector investments in HALEU production. It is critical that downblending is narrowly targeted to meet only near-term needs until a commercial-scale HALEU enrichment plant comes online.

These alternative HALEU production pathways entail unique challenges due to the availability of material, availability of qualified facilities and personnel, and the time and funding required to make material available. These alternative pathways are ultimately stop-gap solutions and new HALEU production capacity is required to meet the commercial needs of advanced reactors.

[91] DOE | Highly Enriched Uranium: Striking a Balance

[92] White House | Transparency in the U.S. Highly Enriched Uranium Inventory

[93] BWXT | BWXT to Manufacture HALEU Feedstock for Advanced Reactors

Appendix B – Separative Work Calculation Derivations

The uranium enrichment process is characterized by the material input and outputs of the enrichment process and the amount of enrichment "work" required to separate the input and output streams. This appendix provides a complete derivation of the separative work calculations used in Section 2.1.1 to calculate the separative work requirements and mass flows for uranium enrichment.

The input for the enrichment process is termed the process "feed" and is characterized by the quantity of material and the enrichment level of the material. The output for the enrichment process is separated into two streams: the process "product" and the process "tails". The "product" is the desired output stream of the enrichment process (with a higher enrichment of U-235 compared with the feed) and the "tails" are the remaining output of the enrichment process (with a lower enrichment of U-235 compared with the feed). Both the product and the tails are characterized by the quantity of material and the enrichment level of the material.

The amount of enrichment "work" necessary to separate the process product and tails from the process feed is termed the separative work required for enrichment. The amount of enrichment "work" is characterized by the separative work unit (SWU). The SWU is a dimensionless number that is calculated based on the mass flows and enrichment of uranium input and output streams.

The material input and outputs of the enrichment process and the amount of separative work for uranium enrichment are described by:

$$W_{SWU} = P \cdot V(x_P) + T \cdot V(x_T) - F \cdot V(x_F) \qquad \text{[Equation B-1]}$$

where:

- W_{SWU} is the amount of "separative work" required by the enrichment process to separate the process inputs (F) into the process outputs (P, T) with specific enrichment levels measured in separative work units (SWU)
- P is the mass of "product" output from the enrichment process measured in kilograms
- $V(x_i)$ is a mathematic value function that describes symmetric logarithmic system behavior based on input x_i, where $x_i = x_P, x_T$, or x_F. The value function is explicitly described below in Equation 2 and plotted in Figure 3.
- x_P is the enrichment of the "product" from the enrichment process (%U-235 enrichment)
- T is the mass of "tailings" output from the enrichment process measured in kilograms
- x_T is the enrichment of the "tailings" from the enrichment process (%U-235 enrichment)
- F is the mass of "feed" input to the enrichment process measured in kilograms
- x_F is the enrichment of the "feed" into the enrichment process (%U-235 enrichment)

The value function $V(x_i)$ in Equation 1 is described by:

$$V(x_i) = (2x_i - 1) \cdot \ln\left(\frac{x_i}{1-x_i}\right) \qquad \text{[Equation B-2]}$$

The value function $V(x_i)$ in Equation B-2 is also plotted in Figure B-1:

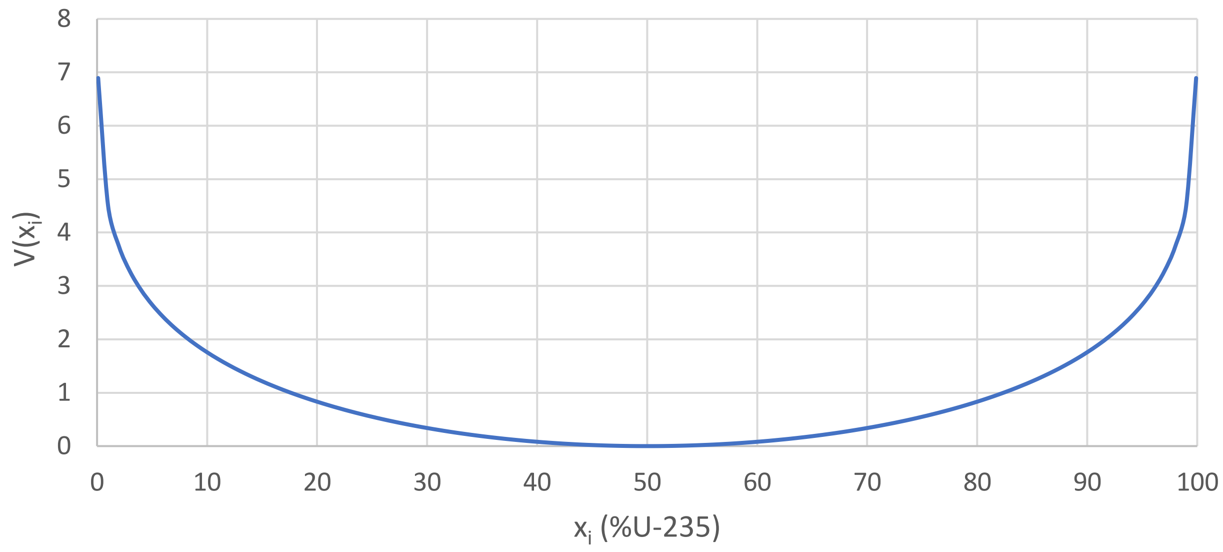

Figure B-1. Value Function $V(x_i)$ for Different Uranium Enrichments (%U-235).

The conceptual relationship between each of the physical variables related to uranium enrichment (Equation B-1) are visualized in Figure B-2

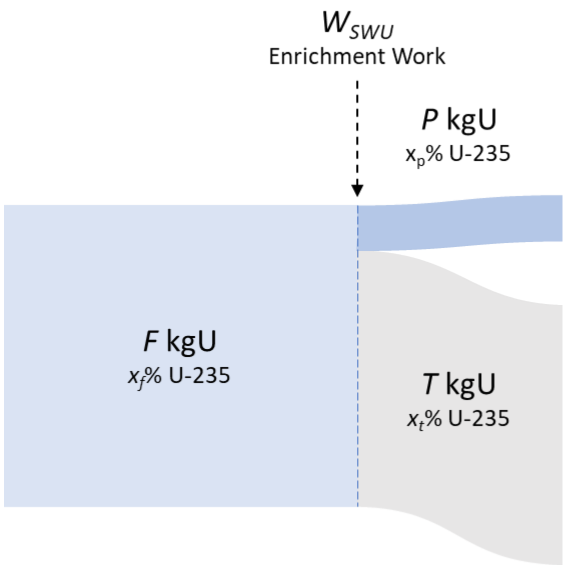

Figure B-2. Uranium Enrichment Variables.

The full equation relating separative work and the process input and output mass flows and enrichments can be characterized:

$$W_{SWU} = P \cdot (2x_P - 1) \cdot \ln\left(\frac{x_P}{1-x_P}\right) + T \cdot (2x_T - 1) \cdot \ln\left(\frac{x_T}{1-x_T}\right) - F \cdot (2x_F - 1) \cdot \ln\left(\frac{x_F}{1-x_F}\right) \quad \text{[Equation B-3]}$$

The separative work equation (Equation 3) is bounded by the conservation of both total uranium mass and U-235 mass in the enrichment process[94]:

$$F = P + T \quad \text{[Equation B-4]}$$

$$F \cdot x_F = P \cdot x_P + T \cdot x_T \quad \text{[Equation B-5]}$$

This set of conservation relations yields a system of 3 equations (Equations B-3, B-4, B-5) dependent on 7 unknown variables ($W_{SWU}, P, x_P, T, x_T, F, x_F$). Specifying the values any four unknown variables in the three equations enables the simultaneous solution of the governing equations.

One specific case to solve for this system of equations is to solve for the number of SWUs (W_{SWU}), the amount of uranium feed input (F), and the uranium tails output (T) based on a defined amount of uranium production output (P), and the enrichment of all input and output streams (x_P, x_T, x_F).For this specific case, the three simultaneous equations to solve then reduce to the following equations:

$$F = P\left(\frac{x_P - x_T}{x_F - x_T}\right) \quad \text{[Equation B-6]}$$

$$T = P\left(\frac{x_P - x_F}{x_F - x_T}\right) \quad \text{[Equation B-7]}$$

$$W_{SWU} = P\left[(2x_P - 1) \cdot \ln\left(\frac{x_P}{1-x_P}\right) + (2x_T - 1)\left(\frac{x_P - x_F}{x_F - x_T}\right) \ln\left(\frac{x_T}{1-x_T}\right) - (2x_F - 1)\left(\frac{x_P - x_T}{x_F - x_T}\right) \ln\left(\frac{x_F}{1-x_F}\right)\right] \quad \text{[Equation B-8]}$$

These equations are the basis for evaluating the mass flows (kg) and separative work (SWU) with different production outputs (kg) and enrichments (% U-235). The mass flows and separative work can then be used to quantify the costs associated with uranium inputs (C_{input}), uranium conversion costs ($C_{convert}$), and enrichment costs (C_{enrich}).

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[94] These equations assume there is no uranium loss during the enrichment process, which can occur due to uranium hold-up or loss in storage systems, pipes, or other facility systems, structures, and components.

Appendix C – Detailed HALEU Production Cost Model

This appendix quantifies and discusses the different cost drivers at each stage of the HALEU production process that feed into the HALEU production cost model. This level of detail behind the HALEU production cost model provides the basis for the HALEU production cost analysis and evaluation of different HALEU production programs.

The following subsections provide the technical basis for a HALEU production cost model and production cost quantification, including:

- Deriving the HALEU production cost model (Section C.1)
- Quantifying costs associated with use of natural uranium as process input material (Section C.2)
- Quantifying uranium conversion costs (Section C.3)
- Quantifying uranium enrichment costs (Section C.4)
- Quantifying costs associated with use of commodity converted natural uranium as process input material (Section C.5)
- Quantifying costs associated with use of commodity converted and low enriched uranium as process input material (Section C.6)
- Quantifying uranium deconversion costs (Section C.7)
- Quantifying HALEU production overhead costs (Section C.8)

It is important to note that this section provides conceptual and quantitative evaluations of uranium enrichment production costs under different conditions that are used in Section 2.3 as the basis for the analysis of HALEU production costs.

C.1 HALEU Production Cost Model

The goal of the DOE HAP is to make enriched and deconverted HALEU available on markets for advanced reactor fuel manufacturers. The final step of advanced reactor fuel production, fuel fabrication, is technology- and producer-specific based on each particular fuel design so the fabrication costs are challenging to characterize generically. A HALEU production cost model is developed that includes costs associated with mining and milling, conversion, enrichment, and deconversion but excludes fuel fabrication costs. This enables generic assessment of the HALEU production costs applicable to all advanced reactors that will use HALEU fuel, and the costs associated with HAP program activities.

The HALEU production costs (excluding fuel fabrication) can be described using the following model:

$$C_{HALEU}\left(\frac{\$}{kgU}\right) = C_{input}\left(\frac{\$}{kgU}\right) + C_{convert}\left(\frac{\$}{kgU}\right) + C_{enrich}\left(\frac{\$}{kgU}\right) + C_{deconvert}\left(\frac{\$}{kgU}\right) + C_{overhead}\left(\frac{\$}{kgU}\right) \quad \text{[Equation C-1]}$$

where:

- C_{HALEU} is the cost (dollars per kilogram of HALEU) of the delivered HALEU at a specific enrichment (equal to or less than 19.9% U-235) in a specific physical form (ceramic or metallic).
- C_{input} is the total cost (dollars per kilogram of HALEU) of mined and milled uranium required to produce one kilogram of uranium at a specified enrichment. This term represents the cost of the feedstock for the HALEU conversion.

- $C_{convert}$ is the total cost (dollars per kilogram of HALEU) required to convert the mined and milled uranium to produce one kilogram of uranium into UF_6 for enrichment. This term represents the cost of the feedstock for the HALEU enrichment.
- C_{enrich} is the total cost (dollars per kilogram of HALEU) required to enrich the converted uranium to the specified enrichment
- $C_{deconvert}$ is the total cost (dollars per kilogram of HALEU) required to deconvert the enriched uranium to produce one kilogram of uranium in a specific physical form (ceramic or metallic). This term represents the cost of the feedstock for the HALEU deconversion.
- $C_{overhead}$ is the total cost (dollars per kilogram of HALEU) associated with any additional overhead activities (e.g., transportation, storage, administration) associated with the processes required to produce one kilogram of uranium at a specified enrichment.

Characterizing each of these cost terms is critical to understanding and estimating the costs associated with HALEU fuel.

C.2 Input Costs (Natural Uranium)

The input costs associated with HALEU production $\left(C_{input}\right)$ in the HALEU production cost model are a function of the total quantity of material required to produce one kilogram of HALEU and the cost of that material per kilogram:

$$C_{input}\left(\frac{\$}{kgU}\right) = F_{NU}\,(kgU) \cdot C_F\left(\frac{\$}{kgU}\right) \qquad \text{[Equation C-2]}$$

where:

- F_{NU} is the quantity of "feed" input to the enrichment process measured in kilograms of uranium. Based on the calculation results in Table 2, the feed input into enrichment using natural uranium is 41.1 kg of feed per kilogram of HALEU product using a typical enrichment process. The exact feed quantity can be calculated for the process based on the relationship described by Equation 6.
- C_F is the cost (dollars per kilogram) of mined and milled uranium. This material costs may be estimated based on spot prices or long-term contracts for uranium. Recent cost data on uranium prices in the United States demonstrate the volatility of prices based on national and international events and well as other inflationary pressures.[95] A baseline value of \$77 / lb U_3O_8 (\$200 / kgU U_3O_8)[96] is used in this analysis for C_F based on typical market values for uranium in 2022 and 2023, but a sensitivity analysis is conducted to understand the impact of changing uranium commodity prices on total HALEU production costs.

In cases where converted or enriched uranium is used as a commodity input directly into the enrichment process, the uranium input costs, and uranium conversion costs can be evaluated together based on the

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[95] EIA | Uranium Marketing Annual Report

[96] The conversion factor between lbs U_3O_8 and kgU is based on calculating and accounting for the mass fraction of oxygen in U_3O_8 and then converting the resulting uranium mass from pounds into kilograms. The conversion factor is approximately 2.6.

commodity price of converted or enriched uranium. This specific cost case is discussed in more detail below.

C.3 Conversion Costs (Natural Uranium)

The conversion cost associated with HALEU production $(C_{convert})$ in the HALEU production cost model is a function of the total quantity of material required to produce one kilogram of HALEU and the cost of that material per kilogram:

$$C_{convert}\left(\frac{\$}{kgU}\right) = F_{NU}\ (kgU) \cdot C_C\left(\frac{\$}{kgU}\right) \quad \text{[Equation C-3]}$$

where:

- F_{NU} is the quantity of “feed” input to the enrichment process measured in kilograms of uranium that must be converted for enrichment. Based on the calculation results in Section 2.1.2, the feed input into enrichment using natural uranium is 41.1 kg of feed per kilogram of HALEU product using a typical enrichment process. The exact feed quantity can be calculated for the process based on the relationship described by Equation 6.
- C_C is the cost (dollars per kilogram of uranium) of conversion services. This cost may be estimated based on spot prices or long-term contracts for uranium conversion services. Recent cost data on uranium conversion worldwide demonstrate the volatility of prices based on national and international events and well as other inflationary pressures.[97] A baseline value of $45 / kgU used in this analysis for C_C based on typical market values for uranium conversion in 2022 and 2023, but a sensitivity analysis is conducted to understand the impact of changing conversion service prices on total HALEU production costs.

In cases where converted or enriched uranium is used as commodity input directly into the enrichment process, the uranium input costs and uranium conversion costs can be evaluated together based on the commodity price of converted or enriched uranium. This specific cost case is discussed in more detail below.

C.4 Enrichment Costs

The enrichment cost associated with HALEU production (C_{enrich}) is a function of the quantity of separative work completed and the cost of each unit of separative work at each step of enrichment:

$$C_{enrich}\left(\frac{\$}{kgU}\right) = W_{SWU_{HALEU}} \cdot C_{SWU_{HALEU}}\left(\frac{\$}{SWU}\right) + W_{SWU_{LEU}} \cdot C_{SWU_{LEU}}\left(\frac{\$}{SWU}\right) \quad \text{[Equation C-4]}$$

where:

- $W_{SWU_{HALEU}}$ is the amount of separative work performed in facilities that can enrich uranium up to 19.75% U-235. The separative work is measured in SWU per one kilogram of HALEU produced.
- $C_{SWU_{HALEU}}$ is the cost of one unit of separative work (SWU) performed in facilities that can enrich uranium up to 19.75% U-235. The cost of the separative work is measured in $/SWU. A baseline value of $1,000 / SWU is used in this analysis for $C_{SWU_{HALEU}}$ based on estimates of new facility

[97] Uranium Price 2022 Year-End Review (investingnews.com)

enrichment costs, but a sensitivity analysis is conducted to understand the impact of changing HALEU enrichment service prices on total enrichment costs.[98]

- $W_{SWU_{LEU}}$ is the amount of separative work performed in facilities that can enrich uranium up to 5% U-235. The separative work is measured in SWU per one kilogram of HALEU produced.
- $C_{SWU_{LEU}}$ is the cost of one unit of separative work (SWU) performed in facilities that can enrich uranium up to 5% U-235. The cost of the separative work is measured in $/SWU. A baseline value of $150 / SWU is used in this analysis for $C_{SWU_{LEU}}$ based on typical market values for uranium enrichment in 2022 and 2023, but a sensitivity analysis is conducted to understand the impact of changing LEU enrichment service prices on total HALEU production costs.[99]

The cost associated with enrichment is divided into three distinct segments due to the effects of existing infrastructure and differing regulatory requirements for uranium enrichment costs.

The separative work cost from an enrichment facility can be conceptually modeled based on the capital costs and operating costs of an enrichment facility. The capital costs represent one-time costs associated with design, licensing, construction, commissioning, and financing of a new enrichment facility. These one-time costs would be amortized over time across facility production. The operating costs represent on-going costs associated with operation and maintenance of the enrichment facility. The annual total cost of production from an enrichment facility (C_{total}) is the sum of an annual amortized capital costs ($C_{capital_{annual}}$) and the annual operating costs ($C_{operating}$):

$$C_{total} = C_{capital_{annual}} + C_{operating} \qquad \text{[Equation C-5]}$$

These two cost categories (capital costs and operating costs) can be conceptually characterized further by differentiating fixed costs and variable costs. Fixed costs do not change with facility capacity or output while variable costs scale with facility capacity or output. Each cost category ($C_{component}$) is the sum of the fixed costs (C_{fixed}) and the product of variable unit cost ($C_{variable}$) and total production ($P_{facility}$):

$$C_{component} = C_{fixed} + C_{variable} \cdot P_{facility} \qquad \text{[Equation C-6]}$$

These two conceptual characterizations of the cost model can be combined to create a generalized facility cost model using the components of the amortized capital costs (C_{cap}) and the annual operating costs (C_{op}):

$$C_{total} = C_{cap_{fixed}} + C_{cap_{variable}} P_{facility} + C_{op_{fixed}} + C_{op_{variable}} P_{facility} \qquad \text{[Equation C-7]}$$

If the facility operates at full capacity (typical for uranium enrichment facilities based on centrifuge design and operation), the average per unit cost of production can be calculated:

$$C_{avg\ unit} = \frac{C_{cap_{fixed_{annual}}} + C_{op_{fixed}}}{P_{facility}} + C_{cap_{variable_{annual}}} + C_{op_{variable}} \qquad \text{[Equation C-8]}$$

[98] More than We Need: Projected World Uranium Enrichment Capacity – Nonproliferation Policy Education Center – Ruaridh Macdonald

[99] Uranium Marketing Annual Report - U.S. Energy Information Administration (EIA)

This equation illustrates three important parametric relationships for the average per unit cost of production specifically related to contract size and length for new production facilities and comparison of near-term and long-term costs for new facilities.

First, the production costs for existing production facilities that have fully amortized their capital costs may be significantly lower than for new production facilities which are still recovering capital costs through production. While this economic relationship is well understood, it is important to note when comparing and evaluating uranium enrichment costs. The production costs for new enrichment facilities will be higher (potentially significantly higher based on the total capital costs and assumed payback period) as compared with existing facilities, but the production cost will reduce overtime as the capital cost is fully amortized and the cost is driven solely by operating costs. The long-term production costs from these new production facilities (post capital cost amortization) will likely be comparable to existing facility production costs and may even be lower if the capital investments increased facility production efficiency. While the production costs for new enrichment facilities may be significantly higher than existing enrichment capacity, these costs can and will decrease over time and are not indicative of long-term production costs.

Second, the production costs for a new production facility will depend significantly on the assumed amortization period for the capital costs. The longer the assumed payback period, the smaller the annualized amortization cost and impact on the average per unit cost of production. Again, while this economic relationship is well understood, it is important to note when comparing and evaluating uranium enrichment costs for new facilities. If a new uranium enrichment facility can amortize capital costs over a longer period of time, it will reduce the cost impact for new production. This highlights the importance of long-term production contracts to create the economic conditions for new capital investments in production capacity. New enrichment facilities required to amortize capital costs over extremely short periods will have higher production costs than facilities with longer guaranteed contracts.

Third, the production costs for facilities will significantly depend on their overall production capacity. Facilities will larger facility outputs will be able to more “spread” fixed costs over larger production than a facility with a small output. Again, this economic relationship is well understood but it is important when assessing the impact of contract size on production costs. Uranium enrichment facilities (and commercial nuclear facilities in general) generally have high fixed costs due to cost drivers such as licensing costs (fixed capital costs) and security (fixed operating costs) that are largely insensitive to production capacity. Uranium enrichment facilities, in particular, are modularly designed and can scale efficiently within a fixed operating envelope. The fixed cost drivers will logarithmically decrease with increasing production and are likely to be a significant cost driver for small production facilities. New enrichment facilities with small production capacity may have significantly higher per unit production costs than facilities with larger production facilities. Additionally, capacity expansion at existing facilities will likely result in lower production costs than new facility construction.

Additional discussion on enrichment costs is provided in Section 2.2.2.

C.5 Combined Input and Conversion Costs (Natural Uranium)

In some cases, uranium feed for enrichment can be purchased on commodity markets as natural uranium already converted to UF_6. In these cases, the input and conversion costs should be combined based on the market prices for converted uranium:

$$C_{input}\left(\frac{\$}{kgU}\right) + C_{convert}\left(\frac{\$}{kgU}\right) = F_{NU}\,(kgU)\cdot C_{F+C}\left(\frac{\$}{kgU}\right) \quad \text{[Equation C-9]}$$

where:

- F_{NU} is the quantity of "feed" input to the enrichment process measured in kilograms of uranium that must be converted for enrichment. Based on the calculations results in Section 2.1, the feed input into enrichment using natural uranium is 41.1 kg of feed per kilogram of HALEU product using a typical enrichment process. The exact feed quantity can be calculated for the process based on the relationship described by Equation 6.
- C_{F+C} is the cost (dollars per kilogram of uranium) of converted natural uranium as UF_6. This cost may be estimated based on spot prices or long-term contracts for UF_6. These values are less commonly reported as commodity or service prices but are available from some private firms.[100] A baseline value of $210 / kgU is used in this analysis for C_{F+C} based on typical market values for converted uranium in 2022 and 2023 and represents a slight mark-up from the sum of the baseline feed and conversion costs (total of $195 / kgU). This is likely due to the additional transportation and overhead associated with purchase of a processed product.

In this case, the converted uranium input material would be transported directly to the enrichment service provider for enrichment.

C.6 Combined Input and Conversion Costs (Low Enriched Uranium)

LEU can be purchased on commodity markets either as an "all in one" transaction or in individual transactions for the three major components (natural uranium, conversion, and LEU enrichment). This LEU can then be used as feed for HALEU enrichment. At today's market prices, LEU costs about $3,000 per kgU.[101] In these cases, the input and conversion costs can be combined based on the commodity costs for converted and enriched uranium:

$$C_{input}\left(\frac{\$}{kgU}\right) + C_{convert}\left(\frac{\$}{kgU}\right) + W_{SWU_{LEU}}\cdot C_{SWU_{LEU}}\left(\frac{\$}{SWU}\right) = F_{LEU}\,(kgU)\cdot C_{F+C+LEU}\left(\frac{\$}{kgU}\right) \quad \text{[Equation C-10]}$$

where:

- F_{LEU} is the quantity of "feed" input of LEU necessary to complete the remainder of the enrichment process measured in kilograms of uranium. Based on the calculations results in Table 1, the feed input into enrichment using LEU at 5% enrichment is 4.5 kg of feed per kilogram of HALEU product using a typical enrichment process. The exact feed quantity can be calculated using the methodology in Section 2.1.
- $C_{F+C+LEU}$ is the cost (dollars per kilogram of uranium) of converted and enriched LEU at 5% enrichment as UF_6. This cost may be estimated based on spot prices or long-term contracts for low enriched UF_6. These values are less commonly reported as commodity or service prices, but are available from some private firms.[102] A baseline value of $4,000 / kgU is used in this analysis for $C_{F+C+LEU}$ based on typical market values for LEU in 2022 and 2023 and represents a slight mark-up from the sum of the baseline feed and conversion costs (Section 2.3.1).

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100 UxC | Data Services
101 UxC: Fuel Cost Calculator for 4.95% LEU.
102 UxC: Data Services

In this case, the converted and enriched uranium input material would be transported directly to the HALEU enrichment service provider for further enrichment.

C.7 Deconversion Costs

The deconversion costs associated with HALEU production ($C_{deconvert}$) are a function of the quantity of material required to produce one kilogram of HALEU and the cost of that material per kilogram:

$$C_{deconvert}\left(\frac{\$}{kgU}\right) = F_{HALEU}\,(kgU) \cdot C_D\left(\frac{\$}{kgU}\right) \qquad \text{[Equation C-11]}$$

where:

- F is the quantity of product output from the enrichment process measured in kilograms of enriched HALEU that must be deconverted following the enrichment process. In this calculation, the quantity of feed is one kilogram since the HALEU costs are calculated on a per kilogram basis.
- C_D is the cost (dollars per kilogram of uranium) of deconversion services. This cost may be estimated based on spot prices or long-term contracts for uranium deconversion services. A baseline value of $2,000 / kgU is used in this analysis for C_D for oxide form deconversion and a baseline value of $4,000 / kgU is used in this analysis for C_D for metallic form deconversion based on previously reported values for uranium fuel cycle activities.[103] A sensitivity analysis is also conducted to understand the impact of changing deconversion service prices on total HALEU production costs.

HALEU deconversion costs are challenging to estimate and likely to be much higher than existing deconversion costs due to the need for new deconversion facilities, the effects of economies of scale for small deconversion facilities, and the challenges of commercializing uranium metallization processes.

Additional discussion on deconversion costs is provided in Section 2.2.3.

C.8 Overhead Costs

The overhead costs associated with HALEU production ($C_{overhead}$) are the total cost (dollars) associated with any additional activities (e.g., transportation, storage, administration) associated with the processes required to produce one kilogram of uranium at a specified enrichment that were incorporated into other cost categories. The overhead costs can be characterized as a sum of different supplementary costs:

$$C_{overhead}\left(\frac{\$}{kgU}\right) = F_{HALEU}\,(kgU) \cdot C_{overhead_{HALEU}}\left(\frac{\$}{kgU}\right) + F_{LEU}\,(kgU) \cdot C_{overhead_{LEU}}\left(\frac{\$}{kgU}\right) + F_{NU}\,(kgU) \cdot C_{overhead_{NU}}\left(\frac{\$}{kgU}\right) + C_{overhead_{other}}\left(\frac{\$}{kgU}\right) \qquad \text{[Equation C-12]}$$

where:

- F_{HALEU}, F_{LEU}, F_{NU} are the quantities of process "feed" material that are handled at different stages of the HALEU production process. Based on the calculations results in Section 2.1.2, the feed stream for natural uranium (F_{NU}) is 41.1 kg of feed per kilogram of HALEU product using a typical enrichment process, the feed stream for LEU at 5% enrichment (F_{LEU}) is 4.5 kg per kilogram of HALEU product using a typical enrichment process, and the final stream of HALEU (F_{HALEU}) is

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1 kg. The exact feed quantity can be calculated for the process based on the relationship described by Equation 6.

- $C_{overhead_{NU}}$, $C_{overhead_{LEU}}$, and $C_{overhead_{HALEU}}$ is the overhead cost (dollars per kilogram of uranium) of additional activities (e.g., transportation, storage, administration) associated with uranium production. These costs will be specific to a specific operation or business process and may be included in the cost of other products or services (e.g., converted and enriched LEU feed may already include transportation costs associated with the natural uranium feed). A baseline value of $5 / kgU is used in this analysis for $C_{overhead_{NU}}$ for natural uranium processing activities, a baseline value of $20 / kgU is used in this analysis for $C_{overhead_{LEU}}$ for LEU processing activities, and a baseline value of $50 / kgU is used in this analysis for $C_{overhead_{HALEU}}$. There is limited public information on the overhead costs associated with uranium processing, so these values are assumed in this report to represent order of magnitude estimates of potential costs.
- $C_{overhead_{other}}$is the total summed overhead cost (dollars per kilogram of uranium) of any other additional activities associated with uranium production that are not captured on a production cost basis by the other cost categories. These costs will be specific to a specific operation or business process and may be included in the cost of other products or services (e.g., converted and enriched LEU feed may already include transportation costs associated with the natural uranium feed). A baseline value of $50 / kgU is used in this analysis for $C_{overhead_{other}}$ for all other commercial activities. There is limited public information on the overhead costs associated with processing, so these values are assumed in this report to represent order of magnitude estimates of potential costs.

These assumed values were based on order of magnitude costs from other advanced reactor fuel cycle studies and help characterize potential overhead cost impacts on total material costs.[104] These costs may be higher or lower depending on the specific enrichment process. A sensitivity analysis is also conducted to understand the impact of changing overhead costs on total HALEU costs. Overhead costs are challenging to estimate due to the variety of different factors that may be included in this cost category. The costs associated with some activities (e.g., transportation and storage) may be included in the cost estimates for other activities, especially if the cost is condensed as a commodity purchase (e.g., converted natural uranium (NU) as a purchased commodity may include the administrative costs associated with mining, milling, and conversion). Estimating the costs requires an understanding of specific business considerations and the commercial factors that affect overhead costs on commercial transactions. This cost category can be expanded based on more detailed understanding of specific process contracts but enables the generic characterization of additional production costs compared with an overall order of magnitude cost of HALEU production.

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Appendix D – HALEU Production Cost Model Inputs

Table D1. Baseline LEU Production Cost Inputs

Cost Variable	Value	Units
F_{NU}	9.81	$\frac{kg\ NU}{kg\ LEU}$
F_{LEU}	1	$kg\ LEU$
C_F	200	$\frac{\$}{kg\ NU}$
C_C	45	$\frac{\$}{kg\ NU}$
C_D	20	$\frac{\$}{kg\ LEU}$
$C_{SWU_{LEU}}$	150	$\frac{\$}{SWU}$
$W_{SWU_{LEU}}$	8.16	$\frac{SWU}{kg\ LEU}$
$C_{overhead_{NU}}$	5	$\frac{\$}{kg\ NU}$
$C_{overhead_{LEU}}$	20	$\frac{\$}{kg\ LEU}$
$C_{overhead_{other}}$	50	$\frac{\$}{kg\ LEU}$

Table D2. Baseline HALEU Production Cost Inputs

Cost Variable	Value	Units
F_{NU}	40.6	$\frac{kg\ NU}{kg\ HALEU}$
F_{LEU}	4.5	$\frac{kg\ LEU}{kg\ HALEU}$
F_{HALEU}	1	$kg\ HALEU$
C_F	200	$\frac{\$}{kg\ NU}$
C_C	45	$\frac{\$}{kg\ NU}$
C_D	2000	$\frac{\$}{kg\ HALEU}$
$C_{SWU_{LEU}}$	150	$\frac{\$}{SWU}$
$C_{SWU_{HALEU}}$	1000	$\frac{\$}{SWU}$
$W_{SWU_{LEU}}$	36.63	$\frac{SWU}{kg\ HALEU}$
$W_{SWU_{HALEU}}$	5.89	$\frac{SWU}{kg\ HALEU}$
$C_{overhead_{NU}}$	5	$\frac{\$}{kg\ NU}$
$C_{overhead_{LEU}}$	20	$\frac{\$}{kg\ LEU}$
$C_{overhead_{HALEU}}$	50	$\frac{\$}{kg\ HALEU}$
$C_{overhead_{other}}$	50	$\frac{\$}{kg\ HALEU}$

Appendix E – HALEU Production Cost Evaluations

Table E1. Baseline HALEU Production Cost with 1-Step Enrichment Process to 19.75% U-235 Enriched Oxide Form (per kg HALEU)

Cost Category	Quantity	Units	Total Cost %
C_{HALEU}	$ 54,860	$/kgHALEU	100%
C_{input}	$ 8,120	$/kgHALEU	15%
F_{NU}	41	kg/kgHALEU	
C_F	$ 200	$/kgNU	
$C_{convert}$	$ 1,827	$/kgHALEU	3%
F_{NU}	40.6	kg/kgHALEU	
C_C	$ 45	$/kgNU	
C_{enrich}	$ 42,520	$/kgHALEU	78%
$C_{enrich_{LEU}}$	$ -	$/kgHALEU	0%
$W_{SWU_{LEU}}$	0	SWU/kgHALEU	
$C_{SWU_{LEU}}$	$ 150	$/SWU	
$C_{enrich_{HALEU}}$	$ 42,520	$/kgHALEU	78%
$W_{SWU_{HALEU}}$	42.52	SWU/kgHALEU	
$C_{SWU_{HALEU}}$	$ 1,000	$/SWU	
$C_{deconvert}$	$ 2,000	$/kgHALEU	4%
F_{HALEU}	1	kg/kgHALEU	
C_D	$ 2,000	$/kgHALEU	
$C_{overhead}$	$ 393	$/kgHALEU	1%
$C_{overhead_{NU_{total}}}$	$ 203	$/kgHALEU	
F_{NU}	40.6	kg/kgHALEU	
$C_{overhead_{NU}}$	$ 5	$/kgNU	
$C_{overhead_{lEU_{total}}}$	$ 90	$/kgHALEU	
F_{LEU}	4.5	kg/kgHALEU	
$C_{overhead_{LEU}}$	$ 20	$/kgLEU	
$C_{overhead_{HALEU_{total}}}$	$ 50	$/kgHALEU	
F_{HALEU}	1	kg/kgHALEU	
$C_{overhead_{HALEU}}$	$ 50	$/kgHALEU	
$C_{overhead_{admin}}$	$ 50	$/kgHALEU	

Table E2. Baseline HALEU Production Cost with 2-Step Enrichment Process to 19.75% U-235 Enriched Oxide Form (per kg HALEU)

Cost Category	Quantity	Units	Total Cost %
C_{HALEU}	\$ 23,725	\$/kgHALEU	100%
C_{input}	\$ 8,120	\$/kgHALEU	34%
F_{NU}	41	kg/kgHALEU	
C_F	\$ 200	\$/kgNU	
$C_{convert}$	\$ 1,827	\$/kgHALEU	8%
F_{NU}	40.6	kg/kgHALEU	
C_C	\$ 45	\$/kgNU	
C_{enrich}	\$ 11,385	\$/kgHALEU	48%
$C_{enrich_{LEU}}$	\$ 5,495	\$/kgHALEU	23%
$W_{SWU_{LEU}}$	36.63	SWU/kgHALEU	
$C_{SWU_{LEU}}$	\$ 150	\$/SWU	
$C_{enrich_{HALEU}}$	\$ 5,890	\$/kgHALEU	25%
$W_{SWU_{HALEU}}$	5.89	SWU/kgHALEU	
$C_{SWU_{HALEU}}$	\$ 1,000	\$/SWU	
$C_{deconvert}$	\$ 2,000	\$/kgHALEU	8 %
F_{HALEU}	1	kg/kgHALEU	
C_D	\$ 2,000	\$/kgHALEU	
$C_{overhead}$	\$ 393	\$/kgHALEU	2%
$C_{overhead_{NU_{total}}}$	\$ 203	\$/kgHALEU	
F_{NU}	40.6	kg/kgHALEU	
$C_{overhead_{NU}}$	\$ 5	\$/kgNU	
$C_{overhead_{lEU_{total}}}$	\$ 90	\$/kgHALEU	
F_{LEU}	4.5	kg/kgHALEU	
$C_{overhead_{LEU}}$	\$ 20	\$/kgLEU	
$C_{overhead_{HALEU_{total}}}$	\$ 50	\$/kgHALEU	
F_{HALEU}	1	kg/kgHALEU	
$C_{overhead_{HALEU}}$	\$ 50	\$/kgHALEU	
$C_{overhead_{admin}}$	\$ 50	\$/kgHALEU	

Table E3. Baseline HALEU Production Cost with 2-Step Enrichment Process to 19.75% U-235 Enriched Metallic Form (per kg HALEU)

Cost Category	Quantity	Units	Total Cost %
C_{HALEU}	$ 25,725	$/kgHALEU	100%
C_{input}	$ 8,120	$/kgHALEU	32%
F_{NU}	41	kg/kgHALEU	
C_F	$ 200	$/kgNU	
$C_{convert}$	$ 1,827	$/kgHALEU	7%
F_{NU}	40.6	kg/kgHALEU	
C_C	$ 45	$/kgNU	
C_{enrich}	$ 11,385	$/kgHALEU	48%
$C_{enrich_{LEU}}$	$ 5,495	$/kgHALEU	21%
$W_{SWU_{LEU}}$	36.63	SWU/kgHALEU	
$C_{SWU_{LEU}}$	$ 150	$/SWU	
$C_{enrich_{HALEU}}$	$ 5,890	$/kgHALEU	23%
$W_{SWU_{HALEU}}$	5.89	SWU/kgHALEU	
$C_{SWU_{HALEU}}$	$ 1,000	$/SWU	
$C_{deconvert}$	$ 4,000	$/kgHALEU	16%
F_{HALEU}	1	kg/kgHALEU	
C_D	$ 4,000	$/kgHALEU	
$C_{overhead}$	$ 393	$/kgHALEU	2%
$C_{overhead_{NU_{total}}}$	$ 203	$/kgHALEU	
F_{NU}	40.6	kg/kgHALEU	
$C_{overhead_{NU}}$	$ 5	$/kgNU	
$C_{overhead_{lEU_{total}}}$	$ 90	$/kgHALEU	
F_{LEU}	4.5	kg/kgHALEU	
$C_{overhead_{LEU}}$	$ 20	$/kgLEU	
$C_{overhead_{HALEU_{total}}}$	$ 50	$/kgHALEU	
F_{HALEU}	1	kg/kgHALEU	
$C_{overhead_{HALEU}}$	$ 50	$/kgHALEU	
$C_{overhead_{admin}}$	$ 50	$/kgHALEU	

Appendix F – HALEU Production Cost Sensitivity Analyses

Detailed results from the HALEU production cost sensitivity analysis in Section 2.3.4 are provided in this appendix.

Each HALEU production cost sensitivity result table shown below provides the calculated change in HALEU production cost (absolute and percentage) for the selected baseline LEU production cost inputs. Baseline costs in each table are highlighted in green. An updated HALEU production cost can be obtained for each varied input by adding the cost change associated with that input to the baseline HALEU production cost of $23,725 / kgU for HALEU enriched to 19.75% and deconverted into an oxide form.

For example, if the natural uranium feed cost was actually $250/kg NU instead of $200/kg NU due to market supply constraints, the updated HALEU production cost estimate would increase by $2,030 / kg HALEU resulting in a total HALEU production cost estimate of $25,755/kgU.

Table F-1. Cost sensitivity analysis for uranium input feed
C_{input} (per kg HALEU)

C_F ($/kg NU)	Change in HALEU Production Cost	
	($/kg)	%
$100	$ (4,060)	-17%
$150	$ (2,030)	-9%
$200	$ -	0%
$250	$ 2,030	9%
$300	$ 4,060	17%

Table F-2. Cost sensitivity analysis for uranium conversion
$C_{convert}$ (per kg HALEU)

C_C ($/kg NU)	Change in HALEU Production Cost	
	($/kg)	%
$25	$ (812)	-3%
$35	$ (406)	-2%
$45	$ -	0%
$55	$ 406	2%
$65	$ 812	3%

Table F-3. Cost sensitivity analysis for LEU enrichment
$C_{enrich_{LEU}}$ (per kg HALEU)

$C_{SWU_{LEU}}$ ($/SWU)	Change in HALEU Production Cost	
	($/kg)	%
$100	$ (1,831.50)	-8%
$125	$ (916)	-4%
$150	$ -	0%
$200	$ 1,831.50	8%
$250	$ 3,663.00	15%

Table F-4. Cost sensitivity analysis for HALEU enrichment
$C_{enrich_{HALEU}}$(per kg HALEU)

$C_{SWU_{HALEU}}$ ($/SWU)	Change in HALEU Production Cost	
	($/kg)	%
$500	$ (2,945)	-12%
$750	$ (1,473)	-6%
$1,000	$ -	0%
$2,000	$ 5,890	25%
$5,000	$ 23,560	99%

Table F-5. Cost sensitivity analysis for HALEU deconversion
$C_{deconvert}$(per kg HALEU)

$C_{deconvert}$ ($/kgU)	Change in HALEU Production Cost	
	($/kg)	%
$1,000	$ (1,000)	-4%
$2,000	$ -	0%
$5,000	$ 3,000	13%
$7,500	$ 5,500	23%
$10,000	$ 8,000	34%

Appendix G – HALEU Material Off-take Agreement Evaluation

This appendix provides full year-by-year program cost assessments for the HALEU Material Off-take Agreements evaluated in Section 4.1.4. Table G-1 summarizes the program operation assumptions for each evaluation. The full year-by-year program costs and material balances are provided in the remainder of this appendix.

Table G-1. Summary of HALEU Material Off-take Agreement Cost Sensitivity Analyses

Sensitivity Analysis Case	Production Schedule	HALEU Purchase Price ($M/MTU)	Demand Schedule	HALEU Sale Price (% of Purchase)	Negotiated Contract Buy-out Used?	Total Required Appropriations with No Revolving Fund ($M)	Total Required Appropriations with Revolving Fund (Note 1) ($M)
Case 1	Baseline	$ 16	Baseline	100%	No	$4,297	$1,009
Case 2	Baseline	$ 20	Baseline	100%	No	$5,297	$1,193
Case 3	Baseline	$ 24	Baseline	100%	No	$6,297	$1,377
Case 4	Baseline	$ 30	Baseline	100%	No	$7,797	$1,653
Case 5	Baseline	$ 36	Baseline	100%	No	$9,297	$1,929
Case 6	Slow Escalating	$ 24	Slow Escalating	100%	No	$6,572	$2,878
Case 7	No Production	$ 24	No Demand	100%	No	$7,153	$5,283
Case 8	No Production	$ 24	No Demand	100%	Yes	$4,853	$3,295
Case 9	Slow Escalating	$ 30	Slow Escalating	100%	No	$8,072	$3,472
Case 10	No Production	$ 30	No Demand	100%	No	$8,653	$6,423
Case 11	No Production	$ 30	No Demand	100%	Yes	$5,903	$3,985
Case 12	Baseline	$ 24	Baseline	80%	No	$6,297	$1,636
Case 13	Baseline	$ 24	Baseline	60%	No	$6,297	$2,697

Note 1) Use of a revolving fund as part of a HALEU Material Off-take Agreement program to reduce appropriation requirements requires the availability of buyout options to secure private capital investments and guarantee capital recovery on new production facilities.

Table G-2. Case 1 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	16	400	6	16	96	19	9.5	610	514
2029	25	0	25	6	0	6	25	16	400	6	16	96	38	19	1,029	837
2030	25	0	25	6	15	21	25	16	400	21	16	336	42	21	1,450	922
2031	25	0	25	6	15	21	25	16	400	21	16	336	46	23	1,873	1,009
2032	25	0	25	6	30	36	25	16	400	36	16	576	35	17.5	2,290	850
2033	25	0	25	6	40	46	25	16	400	46	16	736	14	7	2,697	521
2034	25	25	50	6	60	66	25	16	400	39	16	624	0	0	3,097	297
2035	25	50	75	6	70	76	25	16	400	25	16	400	0	0	3,497	297
2036	25	75	100	6	100	106	25	16	400	25	16	400	0	0	3,897	297
2037	25	100	125	6	110	116	25	16	400	25	16	400	0	0	4,297	297
2038	0	225	225	6	225	231	0	0	0	0	0	0	0	0	4,297	297
2039	0	250	250	6	250	256	0	0	0	0	0	0	0	0	4,297	297
2040	0	275	275	6	275	281	0	0	0	0	0	0	0	0	4,297	297
2041	0	300	300	6	300	306	0	0	0	0	0	0	0	0	4,297	297
2042	0	325	325	6	325	331	0	0	0	0	0	0	0	0	4,297	297

Table G-3. Case 2 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	20	500	6	20	96	19	9.5	710	590
2029	25	0	25	6	0	6	25	20	500	6	20	96	38	19	1,229	989
2030	25	0	25	6	15	21	25	20	500	21	20	336	42	21	1,750	1,090
2031	25	0	25	6	15	21	25	20	500	21	20	336	46	23	2,273	1,193
2032	25	0	25	6	30	36	25	20	500	36	20	576	35	17.5	2,790	990
2033	25	0	25	6	40	46	25	20	500	46	20	736	14	7	3,297	577
2034	25	25	50	6	60	66	25	20	500	39	20	624	0	0	3,797	297
2035	25	50	75	6	70	76	25	20	500	25	20	400	0	0	4,297	297
2036	25	75	100	6	100	106	25	20	500	25	20	400	0	0	4,797	297
2037	25	100	125	6	110	116	25	20	500	25	20	400	0	0	5,297	297
2038	0	225	225	6	225	231	0	0	0	0	0	0	0	0	5,297	297
2039	0	250	250	6	250	256	0	0	0	0	0	0	0	0	5,297	297
2040	0	275	275	6	275	281	0	0	0	0	0	0	0	0	5,297	297
2041	0	300	300	6	300	306	0	0	0	0	0	0	0	0	5,297	297
2042	0	325	325	6	325	331	0	0	0	0	0	0	0	0	5,297	297

Table G-4. Case 3 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	24	600	6	24	144	19	9.5	810	666
2029	25	0	25	6	0	6	25	24	600	6	24	144	38	19	1,429	1,141
2030	25	0	25	6	15	21	25	24	600	21	24	504	42	21	2,050	1,258
2031	25	0	25	6	15	21	25	24	600	21	24	504	46	23	2,673	1,377
2032	25	0	25	6	30	36	25	24	600	36	24	864	35	17.5	3,290	1,130
2033	25	0	25	6	40	46	25	24	600	46	24	1104	14	7	3,897	633
2034	25	25	50	6	60	66	25	24	600	39	24	936	0	0	4,497	297
2035	25	50	75	6	70	76	25	24	600	25	24	600	0	0	5,097	297
2036	25	75	100	6	100	106	25	24	600	25	24	600	0	0	5,697	297
2037	25	100	125	6	110	116	25	24	600	25	24	600	0	0	6,297	297
2038	0	225	225	6	225	231	0	0	0	0	0	0	0	0	6,297	297
2039	0	250	250	6	250	256	0	0	0	0	0	0	0	0	6,297	297
2040	0	275	275	6	275	281	0	0	0	0	0	0	0	0	6,297	297
2041	0	300	300	6	300	306	0	0	0	0	0	0	0	0	6,297	297
2042	0	325	325	6	325	331	0	0	0	0	0	0	0	0	6,297	297

Table G-5. Case 4 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	30	750	6	30	180	19	9.5	960	780
2029	25	0	25	6	0	6	25	30	750	6	30	180	38	19	1,729	1,369
2030	25	0	25	6	15	21	25	30	750	21	30	630	42	21	2,500	1,510
2031	25	0	25	6	15	21	25	30	750	21	30	630	46	23	3,273	1,653
2032	25	0	25	6	30	36	25	30	750	36	30	1080	35	17.5	4,040	1,340
2033	25	0	25	6	40	46	25	30	750	46	30	1380	14	7	4,797	717
2034	25	25	50	6	60	66	25	30	750	39	30	1170	0	0	5,547	297
2035	25	50	75	6	70	76	25	30	750	25	30	750	0	0	6,297	297
2036	25	75	100	6	100	106	25	30	750	25	30	750	0	0	7,047	297
2037	25	100	125	6	110	116	25	30	750	25	30	750	0	0	7,797	297
2038	0	225	225	6	225	231	0	0	0	0	0	0	0	0	7,797	297
2039	0	250	250	6	250	256	0	0	0	0	0	0	0	0	7,797	297
2040	0	275	275	6	275	281	0	0	0	0	0	0	0	0	7,797	297
2041	0	300	300	6	300	306	0	0	0	0	0	0	0	0	7,797	297
2042	0	325	325	6	325	331	0	0	0	0	0	0	0	0	7,797	297

Table G-6. Case 5 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	36	900	6	36	216	19	9.5	1,110	894
2029	25	0	25	6	0	6	25	36	900	6	36	216	38	19	2,029	1,597
2030	25	0	25	6	15	21	25	36	900	21	36	756	42	21	2,950	1,762
2031	25	0	25	6	15	21	25	36	900	21	36	756	46	23	3,873	1,929
2032	25	0	25	6	30	36	25	36	900	36	36	1296	35	17.5	4,790	1,550
2033	25	0	25	6	40	46	25	36	900	46	36	1656	14	7	5,697	801
2034	25	25	50	6	60	66	25	36	900	39	36	1404	0	0	6,597	297
2035	25	50	75	6	70	76	25	36	900	25	36	900	0	0	7,497	297
2036	25	75	100	6	100	106	25	36	900	25	36	900	0	0	8,397	297
2037	25	100	125	6	110	116	25	36	900	25	36	900	0	0	9,297	297
2038	0	225	225	6	225	231	0	0	0	0	0	0	0	0	9,297	297
2039	0	250	250	6	250	256	0	0	0	0	0	0	0	0	9,297	297
2040	0	275	275	6	275	281	0	0	0	0	0	0	0	0	9,297	297
2041	0	300	300	6	300	306	0	0	0	0	0	0	0	0	9,297	297
2042	0	325	325	6	325	331	0	0	0	0	0	0	0	0	9,297	297

Table G-7. Case 6 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	24	600	6	24	144	19	9.5	810	666
2029	25	0	25	6	0	6	25	24	600	6	24	144	38	19	1,429	1,141
2030	25	0	25	6	0	6	25	24	600	6	24	144	57	28.5	2,057	1,625
2031	25	0	25	6	12	18	25	24	600	18	24	432	64	32	2,689	1,825
2032	25	0	25	6	12	18	25	24	600	18	24	432	71	35.5	3,325	2,029
2033	25	0	25	6	12	18	25	24	600	18	24	432	78	39	3,964	2,236
2034	25	0	25	6	12	18	25	24	600	18	24	432	85	42.5	4,606	2,446
2035	25	0	25	6	12	18	25	24	600	18	24	432	92	46	5,252	2,660
2036	25	0	25	6	12	18	25	24	600	18	24	432	99	49.5	5,902	2,878
2037	25	0	25	6	30	36	25	24	600	36	24	864	88	44	6,546	2,658
2038	0	25	25	6	30	36	0	0	0	36	24	864	52	26	6,572	1,820
2039	0	50	50	6	60	66	0	0	0	52	24	1248	0	0	6,572	572
2040	0	75	75	6	60	66	0	0	0	0	0	0	0	0	6,572	572
2041	0	100	100	6	120	126	0	0	0	0	0	0	0	0	6,572	572
2042	0	125	125	6	200	206	0	0	0	0	0	0	0	0	6,572	572

Table G-8. Case 7 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	24	600	6	24	144	19	9.5	810	666
2029	25	0	25	6	0	6	25	24	600	6	24	144	38	19	1,429	1,141
2030	25	0	25	6	0	6	25	24	600	6	24	144	57	28.5	2,057	1,625
2031	25	0	25	6	0	6	25	24	600	6	24	144	76	38	2,695	2,119
2032	25	0	25	6	0	6	25	24	600	6	24	144	95	47.5	3,343	2,623
2033	25	0	25	6	0	6	25	24	600	6	24	144	114	57	4,000	3,136
2034	25	0	25	6	0	6	25	24	600	6	24	144	133	66.5	4,666	3,658
2035	25	0	25	6	0	6	25	24	600	6	24	144	152	76	5,342	4,190
2036	25	0	25	6	0	6	25	24	600	6	24	144	171	85.5	6,028	4,732
2037	25	0	25	6	0	6	25	24	600	6	24	144	190	95	6,723	5,283
2038	0	0	0	6	0	6	0	0	0	6	24	144	184	92	6,815	5,231
2039	0	0	0	6	0	6	0	0	0	6	24	144	178	89	6,904	5,176
2040	0	0	0	6	0	6	0	0	0	6	24	144	172	86	6,990	5,118
2041	0	0	0	6	0	6	0	0	0	6	24	144	166	83	7,073	5,057
2042	0	0	0	6	0	6	0	0	0	6	24	144	160	80	7,153	4,993

Table G-9. Case 8 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	24	600	6	24	144	19	9.5	810	666
2029	25	0	25	6	0	6	25	24	600	6	24	144	38	19	1,429	1,141
2030	25	0	25	6	0	6	25	24	600	6	24	144	57	28.5	2,057	1,625
2031	25	0	25	6	0	6	25	24	600	6	24	144	76	38	2,695	2,119
2032	25	0	25	6	0	6	25	24	600	6	24	144	95	47.5	3,343	2,623
2033	0	0	0	6	0	6	0	0	0	6	24	144	89	284.5	3,627	2,763
2034	0	0	0	6	0	6	0	0	0	6	24	144	83	281.5	3,909	2,901
2035	0	0	0	6	0	6	0	0	0	6	24	144	77	278.5	4,187	3,035
2036	0	0	0	6	0	6	0	0	0	6	24	144	71	275.5	4,463	3,167
2037	0	0	0	6	0	6	0	0	0	6	24	144	65	272.5	4,735	3,295
2038	0	0	0	6	0	6	0	0	0	6	24	144	59	29.5	4,765	3,181
2039	0	0	0	6	0	6	0	0	0	6	24	144	53	26.5	4,791	3,063
2040	0	0	0	6	0	6	0	0	0	6	24	144	47	23.5	4,815	2,943
2041	0	0	0	6	0	6	0	0	0	6	24	144	41	20.5	4,835	2,819
2042	0	0	0	6	0	6	0	0	0	6	24	144	35	17.5	4,853	2,693

Table G-10. Case 9 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	30	750	6	30	180	19	9.5	960	780
2029	25	0	25	6	0	6	25	30	750	6	30	180	38	19	1,729	1,369
2030	25	0	25	6	0	6	25	30	750	6	30	180	57	28.5	2,507	1,967
2031	25	0	25	6	12	18	25	30	750	18	30	540	64	32	3,289	2,209
2032	25	0	25	6	12	18	25	30	750	18	30	540	71	35.5	4,075	2,455
2033	25	0	25	6	12	18	25	30	750	18	30	540	78	39	4,864	2,704
2034	25	0	25	6	12	18	25	30	750	18	30	540	85	42.5	5,656	2,956
2035	25	0	25	6	12	18	25	30	750	18	30	540	92	46	6,452	3,212
2036	25	0	25	6	12	18	25	30	750	18	30	540	99	49.5	7,252	3,472
2037	25	0	25	6	30	36	25	30	750	36	30	1080	88	44	8,046	3,186
2038	0	25	25	6	30	36	0	0	0	36	30	1080	52	26	8,072	2,132
2039	0	50	50	6	60	66	0	0	0	52	30	1560	0	0	8,072	572
2040	0	75	75	6	60	66	0	0	0	0	0	0	0	0	8,072	572
2041	0	100	100	6	120	126	0	0	0	0	0	0	0	0	8,072	572
2042	0	125	125	6	200	206	0	0	0	0	0	0	0	0	8,072	572

Table G-11. Case 10 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	30	750	6	30	180	19	9.5	960	780
2029	25	0	25	6	0	6	25	30	750	6	30	180	38	19	1,729	1,369
2030	25	0	25	6	0	6	25	30	750	6	30	180	57	28.5	2,507	1,967
2031	25	0	25	6	0	6	25	30	750	6	30	180	76	38	3,295	2,575
2032	25	0	25	6	0	6	25	30	750	6	30	180	95	47.5	4,093	3,193
2033	25	0	25	6	0	6	25	30	750	6	30	180	114	57	4,900	3,820
2034	25	0	25	6	0	6	25	30	750	6	30	180	133	66.5	5,716	4,456
2035	25	0	25	6	0	6	25	30	750	6	30	180	152	76	6,542	5,102
2036	25	0	25	6	0	6	25	30	750	6	30	180	171	85.5	7,378	5,758
2037	25	0	25	6	0	6	25	30	750	6	30	180	190	95	8,223	6,423
2038	0	0	0	6	0	6	0	0	0	6	30	180	184	92	8,315	6,335
2039	0	0	0	6	0	6	0	0	0	6	30	180	178	89	8,404	6,244
2040	0	0	0	6	0	6	0	0	0	6	30	180	172	86	8,490	6,150
2041	0	0	0	6	0	6	0	0	0	6	30	180	166	83	8,573	6,053
2042	0	0	0	6	0	6	0	0	0	6	30	180	160	80	8,653	5,953

Table G-12. Case 11 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	30	750	6	30	180	19	9.5	960	780
2029	25	0	25	6	0	6	25	30	750	6	30	180	38	19	1,729	1,369
2030	25	0	25	6	0	6	25	30	750	6	30	180	57	28.5	2,507	1,967
2031	25	0	25	6	0	6	25	30	750	6	30	180	76	38	3,295	2,575
2032	25	0	25	6	0	6	25	30	750	6	30	180	95	47.5	4,093	3,193
2033	0	0	0	6	0	6	0	0	0	6	30	180	89	344.5	4,437	3,357
2034	0	0	0	6	0	6	0	0	0	6	30	180	83	341.5	4,779	3,519
2035	0	0	0	6	0	6	0	0	0	6	30	180	77	338.5	5,117	3,677
2036	0	0	0	6	0	6	0	0	0	6	30	180	71	335.5	5,453	3,833
2037	0	0	0	6	0	6	0	0	0	6	30	180	65	332.5	5,785	3,985
2038	0	0	0	6	0	6	0	0	0	6	30	180	59	29.5	5,815	3,835
2039	0	0	0	6	0	6	0	0	0	6	30	180	53	26.5	5,841	3,681
2040	0	0	0	6	0	6	0	0	0	6	30	180	47	23.5	5,865	3,525
2041	0	0	0	6	0	6	0	0	0	6	30	180	41	20.5	5,885	3,365
2042	0	0	0	6	0	6	0	0	0	6	30	180	35	17.5	5,903	3,203

Table G-13. Case 12 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)	Quantity (MTU)	Price (M$/ MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	24	600	6	19.2	115.2	19	9.5	810	694
2029	25	0	25	6	0	6	25	24	600	6	19.2	115.2	38	19	1,429	1,198
2030	25	0	25	6	15	21	25	24	600	21	19.2	403.2	42	21	2,050	1,416
2031	25	0	25	6	15	21	25	24	600	21	19.2	403.2	46	23	2,673	1,636
2032	25	0	25	6	30	36	25	24	600	36	19.2	691.2	35	17.5	3,290	1,562
2033	25	0	25	6	40	46	25	24	600	46	19.2	883.2	14	7	3,897	1,286
2034	25	25	50	6	60	66	25	24	600	39	19.2	748.8	0	0	4,497	1,137
2035	25	50	75	6	70	76	25	24	600	25	19.2	480	0	0	5,097	1,257
2036	25	75	100	6	100	106	25	24	600	25	19.2	480	0	0	5,697	1,377
2037	25	100	125	6	110	116	25	24	600	25	19.2	480	0	0	6,297	1,497
2038	0	225	225	6	225	231	0	0	0	0	0	0	0	0	6,297	1,497
2039	0	250	250	6	250	256	0	0	0	0	0	0	0	0	6,297	1,497
2040	0	275	275	6	275	281	0	0	0	0	0	0	0	0	6,297	1,497
2041	0	300	300	6	300	306	0	0	0	0	0	0	0	0	6,297	1,497
2042	0	325	325	6	325	331	0	0	0	0	0	0	0	0	6,297	1,497

Table G-14. Case 13 HALEU Material Off-take Agreement Cost Sensitivity Analysis

FY	HALEU Production			HALEU Demand			Program HALEU Purchases			Program HALEU Sales			End of Year HALEU Stockpile (MTU)	Fixed Contracts ($M)	Cumulative Expenditures ($M)	Net Expenditures ($M)
	DOE Sponsored (MTU)	Commercial (MTU)	Total (MTU)	ARDP (MTU)	Other Commercial (MTU)	Total (MTU)	Quantity (MTU)	Price (M$/MTU)	Total (M$)	Quantity (MTU)	Price (M$/MTU)	Total (M$)				
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	100	200	200
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2027	0	0	0	0	0	0	0	0	0	0	0	0	0	0	200	200
2028	25	0	25	6	0	6	25	24	600	6	14.4	86.4	19	9.5	810	723
2029	25	0	25	6	0	6	25	24	600	6	14.4	86.4	38	19	1,429	1,256
2030	25	0	25	6	15	21	25	24	600	21	14.4	302.4	42	21	2,050	1,574
2031	25	0	25	6	15	21	25	24	600	21	14.4	302.4	46	23	2,673	1,895
2032	25	0	25	6	30	36	25	24	600	36	14.4	518.4	35	17.5	3,290	1,994
2033	25	0	25	6	40	46	25	24	600	46	14.4	662.4	14	7	3,897	1,939
2034	25	25	50	6	60	66	25	24	600	39	14.4	561.6	0	0	4,497	1,977
2035	25	50	75	6	70	76	25	24	600	25	14.4	360	0	0	5,097	2,217
2036	25	75	100	6	100	106	25	24	600	25	14.4	360	0	0	5,697	2,457
2037	25	100	125	6	110	116	25	24	600	25	14.4	360	0	0	6,297	2,697
2038	0	225	225	6	225	231	0	0	0	0	0	0	0	0	6,297	2,697
2039	0	250	250	6	250	256	0	0	0	0	0	0	0	0	6,297	2,697
2040	0	275	275	6	275	281	0	0	0	0	0	0	0	0	6,297	2,697
2041	0	300	300	6	300	306	0	0	0	0	0	0	0	0	6,297	2,697
2042	0	325	325	6	325	331	0	0	0	0	0	0	0	0	6,297	2,697