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High-Assay Low Enriched Uranium Demand and Deployment Options

June 2020

HALEU Workshop Report
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Monica C. Regalbuto
Director, Nuclear Fuel Cycle Strategy

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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The report examines anticipated HALEU demand from a variety of sources including the US commercial nuclear industry, potential Department of Defense mobile microreactor needs, Office of Nuclear Energy's advanced reactors demonstrations, Office of Nuclear Energy's advanced test and research reactors, and long-term National Nuclear Security Administration mission. The report addresses findings and recommendations to meet HALEU demand.

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EXECUTIVE SUMMARY

Advanced reactors are being developed for flexible baseload power generation, providing US leadership in nuclear technology, enabling new markets for export, and reducing greenhouse gas emissions. Many of these reactors will require High-Assay Low-Enriched Uranium (HALEU) fuel, which is also used at a small scale for fueling research reactors and for medical isotope production facilities. There are currently no commercial suppliers of HALEU in the United States. In April 2020, the Nuclear Energy Institute (NEI), the Gateway for Advanced Innovation in Nuclear (GAIN), and the Electric Power Research Institute (EPRI) held a virtual workshop on High-Assay Low-Enriched Uranium with the purpose of gathering a team of experts[a] from across the national laboratories and industry to evaluate the anticipated demand for HALEU, the timing of that demand, and to evaluate the options for meeting that demand. This report addresses findings and recommendations to meet HALEU demand.

The current US fuel cycle is based on a low-enriched uranium (LEU) economy. As stated in the recently-published Department of Energy (DOE) report Restoring America's Competitive Nuclear Energy Advantage, the capacity and capabilities of the front end of the US fuel cycle have been eroding since the early 1980s. Developing the HALEU fuel cycle represents an opportunity to reinvigorate domestic mining, conversion[b], enrichment, deconversion[c], and fuel fabrication in the US. Without this development, the US is at risk of ceding the future HALEU market to foreign suppliers (e.g. Russia, China) that can rapidly develop commercial HALEU capacity. Anticipated demand for HALEU comes from a variety of applications. The HALEU needs covered in this report are those of the US commercial nuclear industry, potential Department of Defense (DoD) mobile microreactors, DOE's Office of Nuclear Energy (DOE-NE's) advanced reactors demonstrations, DOE-NE test and research reactors, and long-term National Nuclear Security Administration (NNSA) missions.

To estimate emerging industrial demand, in 2020, the Nuclear Energy Institute (NEI) surveyed eleven reactor designers and developers planning to use HALEU to identify their estimated annual needs through 2030. Projected HALEU needs could reach over 50 MTU/year in 2026. Industry needs are the fastest growing demand for HALEU. The timing for HALEU is influenced by when and which reactor concepts mature toward commercialization.

Several options exist to provide limited quantities of HALEU in the near term for research and development (R&D) and "early movers" until the market develops a commercial enrichment capability in the United States to meet long-term demands. However, these limited quantities are insufficient to meet the projected needs of the industry in the next few years. Commercial investment in the front end of the fuel cycle to support HALEU production will not be made on a speculative basis. Transitioning from "early movers" to a "sustainable" market would be a gradual approach referred to as the "evolution" phase. Relying upon market forces and demand will not be enough to create the needed HALEU fuel cycle capabilities in the United States at the time the industry will require it. The HALEU market would reach the sustainable phase when (1) a large enough customer base is evident, which will lead to securing long-term purchase agreements and (2) fuel procurement models and fuel cycle infrastructure financing tools evolve. The timing of when this point will be achieved is not predictable.

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a. https://gain.inl.gov/SiteAssets/2020HALEU_Workshop/GAIN-EPRI-NEI_HALEU_WebinarRegistration.pdf

b. Conversion in this context means the chemical conversion of uranium from its natural oxide form into uranium hexafluoride (UF_6). This is the chemical form used in centrifuge enrichment.

c. Deconversion refers to the chemical conversion of UF_6 to uranium in oxide form. In the LEU fuel cycle, this step is traditionally done in fuel fabrication facilities. However, because of the different fuel forms for advanced reactors and the difficulties associated with shipping HALEU in UF_6 form, this process might be carried out at an enrichment facility in a HALEU supply chain.

Understanding the physical security requirements and capital costs for enrichment activities at various levels are key to the deployment of a HALEU supply chain. HALEU enrichment needs range from 5–19.75%. Over 90% of the separative work required to enrich natural uranium from 0.72% to 19.75% U-235 is utilized in the 0.72%–10% enrichment range. The range above 5% and below 10%, sometimes referred to as LEU+ (or LEU "plus") can be enriched in a physical security Category III facility[d]. Enrichments of 10% and above must be conducted in a physical security Category II facility, which requires significant capital investments to license, build, secure, and operate. Utilizing existing LEU (expanded to LEU+) enrichment infrastructure will significantly decrease the size of a Category II facility, resulting in lower costs and more competitive production of HALEU. Deconversion of HALEU enriched to 10% or higher must also be conducted in a physical security Category II facility. Co-location of HALEU facilities (enrichment, deconversion, and fuel fabrication) with an LEU enriching facility decreases the cost of transportation and leverages security costs. Co-location of facilities will result in the most economic HALEU production model.

Development of future HALEU capabilities should consider all potential applications: nuclear industry, research and test reactors, and long-term applications. Currently, predictable "high-fidelity" demand of HALEU greater than 10% U-235 enriched in the next 10 years is driven by medical isotope production, highly enriched uranium (HEU) to HALEU research reactor conversion, the DoD microreactor demonstration, DOE's advanced reactor demonstration, and DOE test and research reactors. It is predicted that by the mid-2020's, approximately 22 MTU will be needed for initial high-fidelity core loadings. By that time, annual high-fidelity HALEU demand is estimated to be between 8–12 MTU.

To accelerate development of a sustainable HALEU supply capability, an initial public/private partnership is recommended to address the high-fidelity HALEU market plus a percentage of the projected commercial demand. The private sector could incrementally expand the capacity in a modular fashion as a sustainable market develops. Given the variety of HALEU applications, the initial HALEU capability must be flexible and able to accommodate the following:

- Uranium enriched up to 10% U-235 as the feed
- Enrichments of U-235 varying from 10 to 19.75%
- Supply HALEU at a minimum annual rate of 12 MTU
- Modular design concepts to accommodate future growth
- Deconversion of UF_6 to a form (e.g., uranium oxide) suitable for production of a variety of uranium fuel forms, to include oxides, metal and alloys, and nitrides and carbides.

A pricing model that accounts for the added value of going from LEU (or LEU+) to HALEU should be established by the partnership. In addition, given the HALEU "high-fidelity" demand is mainly driven to support government agencies' projects and mission needs, a mechanism such as a lease model, wholesaler, or reserve should be developed to make HALEU available to support commercial needs.

d. Category III is an NRC designation for fuel cycle facilities that handle material of "low strategic significance". https://www.nrc.gov/reading-rm/basic-ref/glossary/categories-of-fuel-facilities.html

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ACRONYMS

ATF	accident tolerant fuel
DoD	Department of Defense
DOE	Department of Energy
DOE-NE	DOE's Office of Nuclear Energy
EBR-II	Experimental Breeder Reactor-II
HALEU	high-assay low-enriched uranium
INL	Idaho National Laboratory
LWR	Light Water Reactor
MTU	Metric Tons Uranium
NEI	Nuclear Energy Institute
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
R&D	research and development
RFI	Request for Information
TRISO	tristructural isotropic
vSMRs	very small modular reactors
VTR	Versatile Test Reactor

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High-Assay Low Enriched Uranium Demand and Deployment Options

1. INTRODUCTION

Advanced reactors are being developed for flexible baseload power generation, providing US leadership in nuclear technology, enabling new markets for export, and reducing greenhouse gas emissions. Many advanced reactors will require higher enrichments and fuel forms that differ from those currently manufactured for the Light Water Reactors (LWRs). For example, the current generation of LWRs uses fuel enriched to less than 5% uranium-235 as UO_2 ceramic pellets encased in zirconium cladding rods. In contrast, many advanced non-LWR designs have compact designs and/or longer core lifetimes between refueling, requiring fuel with higher enrichment than conventional LWR fuel. In addition, fuel with enrichments greater than 5% are also being considered for use in advanced fuels now being designed for the existing LWR fleet (e.g., metallic fuels and accident tolerant fuels [ATFs]).

The current US fuel supply infrastructure is based on low enriched uranium (LEU) (i.e., less than 5% enrichment). Most of the advanced reactors will require fuel with uranium that is enriched in U-235 in the 5–19.75% range and is commonly referred as HALEU. HALEU is also used for fueling research reactors and for medical isotope production facilities. There are currently no commercial suppliers of HALEU in the United States. The finite supply of material available for downblending to HALEU, without an enrichment capability, and a growing number of end-users causes uncertainty among advanced reactors as well as with international partners that rely on the U.S. as a supplier and many of whom support U.S. nonproliferation objectives. In April 2020, the Nuclear Energy Institute (NEI), the Gateway for Advanced Innovation in Nuclear (GAIN), and the Electric Power Research Institute (EPRI) held a virtual workshop on High-Assay Low-Enriched Uranium with the purpose of gathering a team of experts from across the national laboratories and industry to evaluate the anticipated demand for HALEU, the timing of that demand, and to evaluate the options for meeting the demand[e]. This report addresses options for developing capabilities to produce HALEU in the US to support industrial deployment of advanced reactors and other future DOE needs without jeopardizing the Department's international and national security commitments.

2. THE FRAGMENTED FRONT END OF THE US FUEL CYCLE

To provide options to address HALEU demands, we need to recognize the current state of LEU capabilities in the US. The nuclear fuel cycle is referred to as the activities or processes necessary to produce fuel for a nuclear reactor. They consist of (1) the front end—uranium mining, conversion, enrichment, deconversion and fuel fabrication—and (2) the back end—spent fuel storage and permanent disposal. The current US fuel cycle is based on an LEU economy. As stated in the recently-published White House Nuclear Fuel Working Group report[f], the front end of the US fuel cycle capacity has been eroding since the early 1980s. In 2018, 89% of the uranium loaded into US nuclear reactors was from foreign origin[g]. The only conversion facility in the US is idle due to market conditions, and only one enrichment facility with a current capacity to enrich one-third of US reactor requirements is operated domestically.

In contrast, other nations recognize that market prices for uranium, conversion, and enrichment are too low to support a purely commercial venture and that there is a national security, nonproliferation, and geostrategic value in such capabilities. Outside the US, fuel cycle facilities are overwhelmingly state

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e. https://gain.inl.gov/SitePages/GAINWebinarSeries.aspx

f. https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring%20America%27s%20Competitive%20Nuclear%20Advantage-Blue%20version%5B1%5D.pdf

g. https://www.eia.gov/uranium/marketing/pdf/umar2018.pdf owned/sponsored (e.g., Russia, China). These countries view fuel cycle capabilities as a strategic national asset, an extension of their foreign policy, and a source of global influence. It is important to understand the need to develop and maintain a reliable supply chain. An integrated US approach to developing a competitive front-end nuclear capability is in the best interest of the nation and increases the resilience necessary to maintain domestic industrial needs. Developing the HALEU fuel cycle represents an opportunity to reinvigorate domestic mining, conversion, enrichment, deconversion, and fuel fabrication in the US. Without this development, the US is at risk of ceding the future HALEU market to foreign suppliers (e.g., Russia, China) that can rapidly develop commercial HALEU capacity.

3. HALEU ANTICIPATED DEMAND

Anticipated demand for HALEU comes from a variety of applications:

- Introduction of new fuel concepts for existing LWRs seeking improvements in reactor economics through higher burn-up rates and extended operating cycles
  - ATF
  - New metallic fuels
- Deployment of Generation IV and other advanced reactors
- Mobile microreactors
- Research and test reactors
- Medical isotope production
- Space missions
- National security

The HALEU needs covered in this report are those of the US commercial nuclear industry, upcoming Department of Defense (DoD) mobile microreactors and DOE's Office of Nuclear Energy (DOE-NE) advanced reactor demonstrations, DOE-NE's test and research reactors, and long-term National Nuclear Security Administration (NNSA) missions.

3.1 Industrial Applications

Industry requirements include ATF and new metallic fuels for the existing fleet and deployment of Generation IV and other advanced reactors. This is the fastest growing demand for HALEU. Within the next 10 years, many designers of new advanced reactors will require HALEU for fuel qualification and reactor development and demonstration. In the longer-term, the owners/operators of such reactors will require access to HALEU.

Initially, a reactor developer requires small quantities of HALEU to fabricate fuel samples for testing and analyses to validate and finalize their designs. If successful, the reactor developer will then require engineering-scale quantities to fuel demonstration reactors and in some cases full-scale quantities.

To estimate emerging industrial demand, the Nuclear Energy Institute (NEI) surveyed eleven reactor designers and developers planning to use HALEU to identify their estimated annual needs (Table 1) through 2030. The values listed assume that each company will commercialize their design and as such provides an upper bound for the expected demand of HALEU for industry applications. Although not every possible developer was included, projected HALEU needs could reach over 50 MTU/year in 2026.

Table 1. NEI 2020 survey HALEU results[h].

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Annual HALEU MTU	2.8	3.3	9.7	12	32	64.2	32.7	50	81.7	137.3

3.2 DoD Mobile Microreactors

DoD is evaluating the use of mobile microreactors to replace petroleum-based fuel systems to provide power at a DoD site or for deployed forces at forward and remote sites. On January 22, 2019, the DoD Office of the Under Secretary of Defense for Research and Engineering, acting through the Strategic Capabilities Office, issued an updated Request for Information (RFI) seeking information on "small mobile nuclear reactor concept designs" that would provide 1-10 MWe of electric power generation.[i] In addition to small mobile concepts, DoD is considering additional uses for very small modular reactors (vSMRs) installed at bases. Given that the same vendors will be developing power producing technology that could be used for either civil or defense applications, we consider the DoD HALEU demand beyond the development phase as contributing to the industrial demand for HALEU, included in Table 1.

3.3 DOE-NE Research and Test Reactors

DOE is developing the Versatile Test Reactor (VTR), a national user facility intended to enable US advanced technologies and reactor development through accelerated irradiation testing of advanced fuels and materials, instrumentation, and sensors. In February 2019, the Deputy Secretary approved the Mission Need for the VTR Program, formally achieving Critical Decision-0. DOE has completed VTR's conceptual design with a core using a uranium plutonium zirconium (U/Pu/Zr) based fuel. Future fuel compositions could be adjusted to utilize uranium in the amount of approximately 2 MTU of HALEU annually.

3.4 Long-term NNSA Missions

DOE/NNSA requires a reliable supply of enriched uranium (LEU, HALEU, and highly enriched uranium [HEU]), with some of these needs requiring uranium free from foreign legal obligations, to support its missions. DOE/NNSA is responsible for producing HALEU for fueling research reactors converted from HEU fuel to HALEU fuel, space reactors, medical isotope production facilities, and other national security needs. Reported NNSA enriched uranium needs are:

- HALEU needs for research reactors and isotope production – 3 to 7 MTU annually from 2020 to 2034 and 7 to 9 MTU annually beginning in 2034[j]
- HEU for space reactors – less than 60kg annually from 2020-2065[k]
- LEU (4.75% U-235) Tritium sustainment – 56 MTU of newly enriched annually beginning 2038[l]
- Other national security needs – future HEU fuel for naval reactors by approximately 2060.

h. https://gain.inl.gov/HALEU_Webinar_Presentations/Forms/AllItems.aspx

i. https://www.fbo.gov/index?id=a11aa31c8f828400d5c5d94b0e972319

j. "Based on several assumptions regarding conversion of HEU reactors to LEU, the Department projects demand for High-Assay LEU to be 3 to 7 MTU annually between 2019 and 2034 and 7-9 MTU annually beginning in 2034." Q&A document for RFI DE-SOL-008552 for Supply of Enriched Uranium. See the supplemental Q&A Document released as part of the RFI process.

k. US DOE, NNSA Request for Information DE-SOL-0008552 for Supply of Enriched Uranium, 2017.

l. "Unobligated and unencumbered LEU as UF_6 at approximately 4.75% uranium-235 enrichment in sufficient quantities to supply one pressurized water reactor reload (approximately 42.3 metric tons uranium) every year for two years and two reactor reloads every third year." US DOE, NNSA Request for Information DE-SOL-0008552 for Supply of Enriched Uranium, 2017.

DOE/NNSA currently meets some of its HALEU needs by downblending its excess HEU; however, the available supply of excess HEU that can be downblended to HALEU is limited, as a considerable portion of HEU is downblended to LEU for defense needs. NNSA is currently executing an Analysis of Alternatives to determine the long-term solution to its enriched uranium needs.

4. ADDRESSING HALEU TIMING

The increase demand for HALEU will be mainly driven by the deployment of advanced reactors which can be described in three distinct stages:

- Fuel research and development
- Initial core demonstration
- Commercial needs

During the research and development (R&D) stage, small quantities in the gram to kilogram scale are necessary for fuel testing and qualification. The demand increases as developers move to initial core demonstrations where the demand for HALEU falls in the range of hundreds of kilograms to metric tons, depending on the reactor design. As prototype and full-scale concepts evolve and mature, and commercial deployment is achieved, the demand for HALEU increases into the hundreds of metric tons range.

Advanced reactor development and deployment schedules vary. Some concepts utilize fuels that have already been qualified, while others offer innovative fuel designs. Licensing activities are also at different stages and vary from pre-application interactions to submitted applications with the Nuclear Regulatory Commission (NRC), as well as engagement with the Canadian regulator. One can quantify the potential demand for HALEU for each of the new reactor concepts but identifying the exact time when it would be needed is challenging. If the US had the capability to produce HALEU, HALEU producers would adjust the capacity or throughput of an enrichment facility to meet the demand as it grows. The timing for HALEU is influenced by when and which reactor concepts mature toward commercialization for a diverse number of applications, as shown in Figure 1.

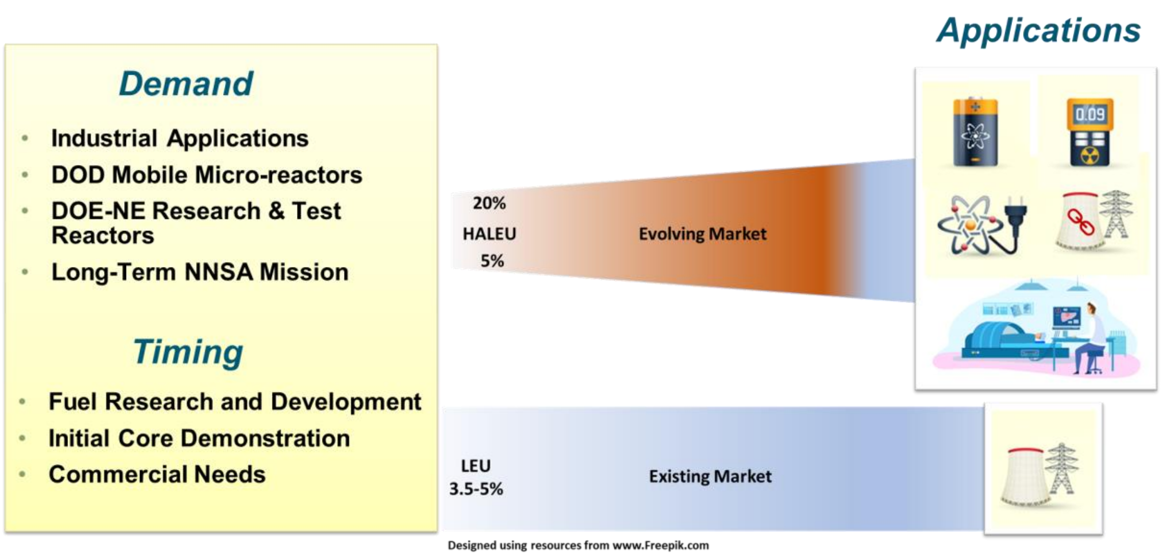

Figure 1. HALEU timing and demand is driven by diverse applications.

The US currently has no commercial facilities to produce HALEU; however, several options exist to provide limited quantities of HALEU in the near term for R&D and "early movers" until the market develops a commercial enrichment capability to meet long-term demands. However, these limited quantities are insufficient to meet the projected needs of the industry in the next few years. Commercial investment in the front end of the fuel cycle to support HALEU production will not be made on a speculative basis. As shown in Figure 2, transitioning from "early movers" to a "sustainable" market would be a gradual approach, the "evolution" phase.

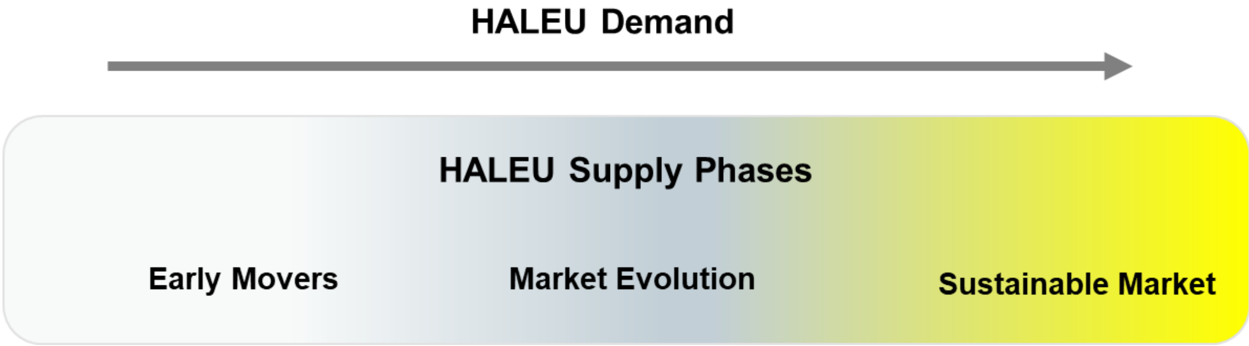

Figure 2. HALEU supply phases.

In a traditional supply and demand model, commodity quantities of HALEU would not be produced until they are justified by demand. When only a limited supply of commercially HALEU is available, it results in a very high cost of fuel for initial cores. This is a penalty to those reactor developers that are "early to the market."

HALEU can be produced in two ways (Figure 3): by blending current or recovered HEU with uranium of a lower enrichment (downblending) or by uranium enrichment. Currently there are very limited HEU stocks available for downblending beyond those already obligated for NNSA missions. A limited supply of HALEU is available from recovered and downblended HEU stock at INL. There are currently four commercial entities in the US who could produce HALEU by downblending or enrichment, provided favorable market conditions exist.

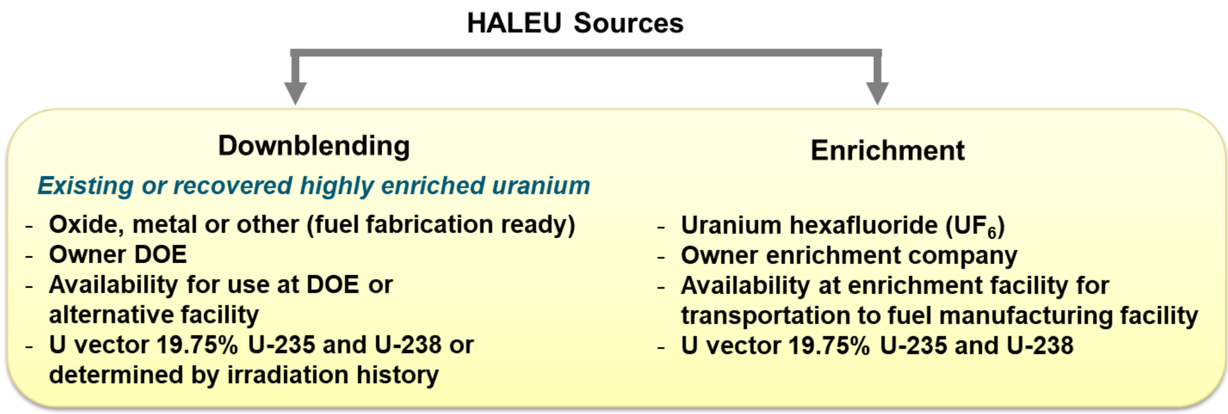

Figure 3. HALEU Sources.

4.1 Early Movers

An aggressive deployment schedule is being pursued by advanced reactor developers eager to penetrate an evolving world market. There are a few avenues that support early deployment, including private investors, DOE-NE[m], and DoD[n] demonstrations. Various approaches could meet HALEU demand in this phase[o].

Pursued at INL, and potentially expanded at the Savannah River Site, an approach is to recover HEU from used fuel and downblends to HALEU. At INL, HEU from spent Experimental Breeder Reactor-II (EBR-II) driver fuel is recovered and downblended to just under 20% enrichment. This material is currently available through DOE and is ideally suited for use in fast spectrum reactors. For thermal spectrum reactor applications, the material requires further polishing to remove radiological and elemental contaminants. A total of approximate 10 MTU of 19.75% enriched materials would be available from EBR-II. In addition, research reactor fuel (e.g., Advanced Test Reactor or High-Flux Isotope Reactor) fuel could be processed and the HEU recovered and downblended. Processing Advanced Test Reactor spent fuel could provide an additional 15–20 MTU of 19.75% enriched HALEU. Additionally, approximately 19 MTU of 19.75% enriched HALEU could be made available from fuel take-back processing at the Savannah River Site.

An alternative downblending approach from BWX Technologies, Inc., focuses on utilizing limited supplies of HEU owned by the US government that were declared excess or surplus to defense programs and are therefore unusable for NNSA's defense missions. Should the US government decide to pursue this option, BWX Technologies could make investments to establish the capability to downblend this material using unobligated[p] natural or depleted uranium to maintain its unobligated designation, or downblended with foreign-origin 5% enriched uranium if there is no need for the material to remain unobligated. The US HEU is reserved for strategic programs only, but limited supplies of the HEU could be made available for downblending or swapped for other materials that meet strategic objectives. This approach could produce up to 10 MTU of 19.75% enriched HALEU annually, dependent on the HEU enrichment level.

Another approach supports production of HALEU between 5% and 10% enrichment by utilizing current URENCO USA commercial enrichment facilities. This requires a modification to their NRC license, which may be achievable within 24 months. Annual capacity would be determined by market needs. An additional near-term enrichment effort currently being supported by DOE-NE is the ongoing demonstration of the AC-100M centrifuge, a US-origin technology, to produce HALEU in support of establishing a sustainable commercial source of unobligated material. American Centrifuge Operating LLC, a subsidiary of Centrus Energy, has a 16-machine cascade of AC-100M units at DOE's Portsmouth Site in Piketon, Ohio, as part of its ongoing enrichment demonstration. This demonstration will produce up to 600 kg of UF_6 enriched to 19.75% by 2022. Demonstration cascade capacity is approximately 1 MTU/yr. A third enricher, Global Laser Enrichment, is exploring the potential to modify current deployment plans to accelerate HALEU capability, though on a smaller scale than commercial centrifuge enrichment.

4.2 Market Evolution

Without a commercial source of HALEU, only government or foreign stocks would be available to support reactor deployment. As shown in the previous section, government stocks are limited. When demand for core demonstrations exceeds available government stocks, additional HALEU capability must

m. Request for Information/Notice of Intent (RFI/NOI)

n. https://www.fbo.gov/index?id=a11aa31c8f828400d5c5d94b0e972319

o. https://gain.inl.gov/HALEU_Webinar_Presentations/Forms/AllItems.aspx

p "Unobligated" material in this context refers to uranium that is free from peaceful use restrictions placed upon it by its country of origin. This is often called "U.S. flagged" material.

be deployed. As reactor developers build prototypes to demonstrate performance and market viability, the demand for HALEU would increase, although not to the amount necessary to justify investments in the HALEU fuel cycle infrastructure. Justification for investments in HALEU capability would be driven by long-term purchase agreements, not by the aggregate of initial demonstration cores or even a few commercially deployed reactors.

Relying upon market forces and limited initial demand alone will not be enough to create the needed HALEU fuel cycle capabilities at the time the industry will require it. Unlike the 1950s when LWRs were being developed and the government was the sole supplier of LEU, the transition from an LEU to a HALEU economy does not require starting from zero. It could be achieved by "right-sizing" an initial HALEU fuel cycle infrastructure investment. This investment could be done in partnership with the government and used to support its long-term enrichment strategic mission needs. The government could support building capacity required for its own purposes, leaving the private sector to incrementally expand the capacity in a modular fashion as a sustainable market develops. Details of how to address this phase are given in the next sections.

4.3 Sustainable Market

As deployment of HALEU reactors becomes more prevalent, demand for HALEU will increase, supporting the evolution of the HALEU market. Increase in demand is necessary, but it is not the only variable that will drive the HALEU market. Another important variable is advanced reactor economics which differ in many cases from current LWRs and must be addressed in order to inform a sustainable HALEU market.

The cost of nuclear power generation has typically been dominated by large capital reactor costs. One of the goals of advanced reactor developers is to reduce capital costs by utilizing simpler, inherently safe designs that may allow for significantly lower capital costs. For example, an expensive containment vessel may not be needed as the layers of safety will be built into the fuel (e.g., TRISO) as it is fabricated. These new fuel fabrication techniques, combined with the added costs of HALEU enrichment, will make the fuel a somewhat larger share of the overall levelized cost of electricity than is the case for today's reactors. In addition, some advanced reactors have much longer fuel cycles. Some microreactors, for example, are envisioned to go decades without refueling. This means the entire fuel load must be purchased upfront with the reactor and in some cases may exceed capital costs.

The HALEU market would reach the sustainable phase when (1) a large enough customer base is evident, which will lead to securing long-term purchase agreements and (2) fuel procurement models and fuel cycle infrastructure financing tools evolve. The timing of when this point will be achieved is not predictable.

5. INTEGRATED HALEU SUPPLY STRATEGY

As discussed in Section III, there are multiple current and emerging applications for HALEU. New fuel concepts for existing LWRs seeking improvements in reactor economics through higher burn-up rates and extended operating cycles such as ATF and new metallic fuels, require enrichments less than 10% U-235. Some advanced reactor concepts have similar needs. As shown in Figure 4, the most impacted facilities that support a HALEU fuel cycle economy are enrichment, deconversion, and fuel fabrication. If facilities are not co-located, there is also a significant impact from transportation.

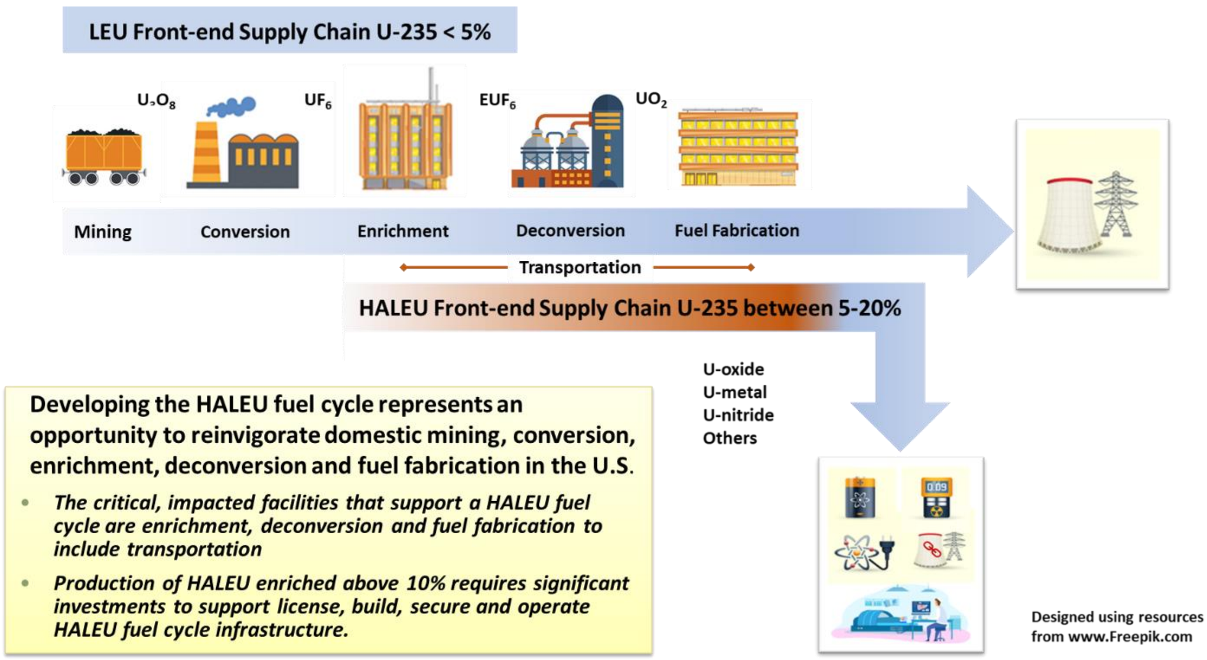

Figure 4. Integrated uranium supply chain.

Understanding the physical security requirements and capital costs for enrichment at various levels are key to the deployment of a HALEU supply chain. HALEU enrichment needs range from 5–19.75%. As shown in Figure 5, over 90% of the separative work required to enrich natural uranium from 0.72% to 19.75% U-235 is utilized in the 0.72% - 10% enrichment range. Enrichments up to 10% may be conducted in a physical security Category III facility. Because enrichments of less than 10% can be done in the same physical security category building as those used to enrich LEU, HALEU enriched from 5% to 10% is commonly referred as LEU+. Enrichments above 10% must be conducted in a physical security Category II facility which requires significant capital investments to license, build, secure, and operate. It is important to note that only less than 10% of the separative work needs to be conducted in a Category II facility. Moving from an LEU to HALEU economy requires investment in Category II facilities, but these facilities have a much smaller footprint compared to current Category III LEU enrichment facilities.

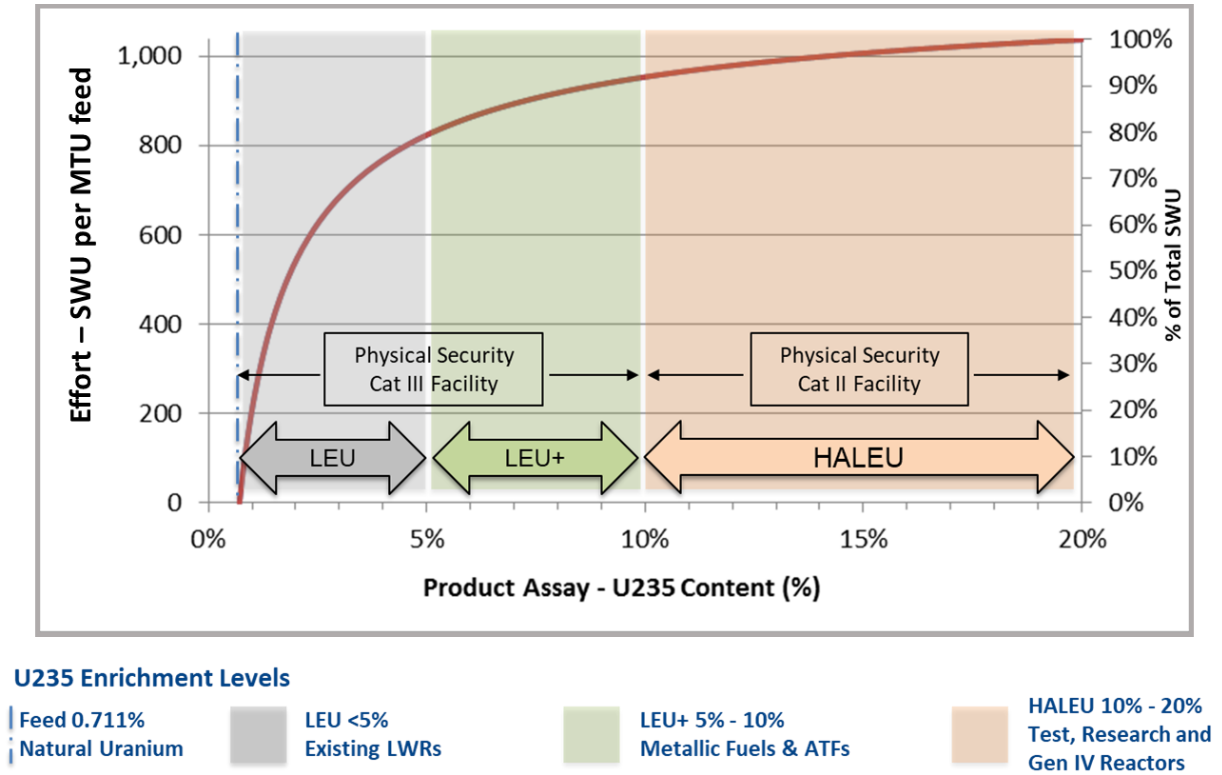

Figure 5. Cumulative SWU required for given U-235 enrichment[q]. HALEU enriched from 5% to 10% is commonly referred as LEU+.

Utilizing LEU (expanded to LEU+) enrichment infrastructure will significantly decrease the size of a Category II facility, resulting in lower costs and more competitive production of HALEU. The output of the enrichment facility is in the form of UF_6, which is transported to a fuel fabrication facility, where the UF_6 is deconverted to a form suitable for fuel fabrication. Deconversion of HALEU enriched above 10% must also be conducted in a physical security Category II facility. High-throughput, cost-competitive transportation options for HALEU UF_6 are currently being developed. However, handling of UF_6 cylinders is a batch operation that adds time and cost to the production of fuels. Minimizing the handling of UF_6 HALEU cylinders would result in more efficient operations and lower fuel fabrication costs. Co-location of HALEU facilities (enrichment, deconversion and fuel fabrication) with an LEU enriching facility decreases the cost of transportation and leverages security costs. Co-location of facilities will result in the most economic HALEU production model.

6. “RIGHT-SIZED” INITIAL CAPABILITY

Development of future HALEU capabilities should consider all potential applications: nuclear industry, research and test reactors, and long-term applications. Currently, predictable demand of HALEU greater than 10% U-235 enriched in the next 10 years is driven by medical isotope production, HEU to HALEU research reactor conversion, the DoD microreactor demonstration, DOE’s advanced reactor demonstration, and DOE test and research reactors.

Near-term, predictable HALEU “high-fidelity” demand mainly supports government agencies’ demonstration projects and mission needs. Some of them are currently met by downblending limited HEU government-owned stocks. Others, like the early movers participating in demonstration programs, are

q. URENCO USA https://gain.inl.gov/HALEU_Webinar_Presentations/Forms/AllItems.aspx being addressed by the various approaches described in Section 5.1 and summarized in Figure 6. By mid-2020's approximately 22 MTU are predicted to be needed for initial core loadings to support DoD and DOE's reactor demonstrations and DOE test and research reactors. The high-fidelity HALEU demand is estimated to be between 8-12 MTU annually for the next 10 years, as shown in Table 2. The annual demand includes medical isotope production and HEU to HALEU research reactor conversion needs.

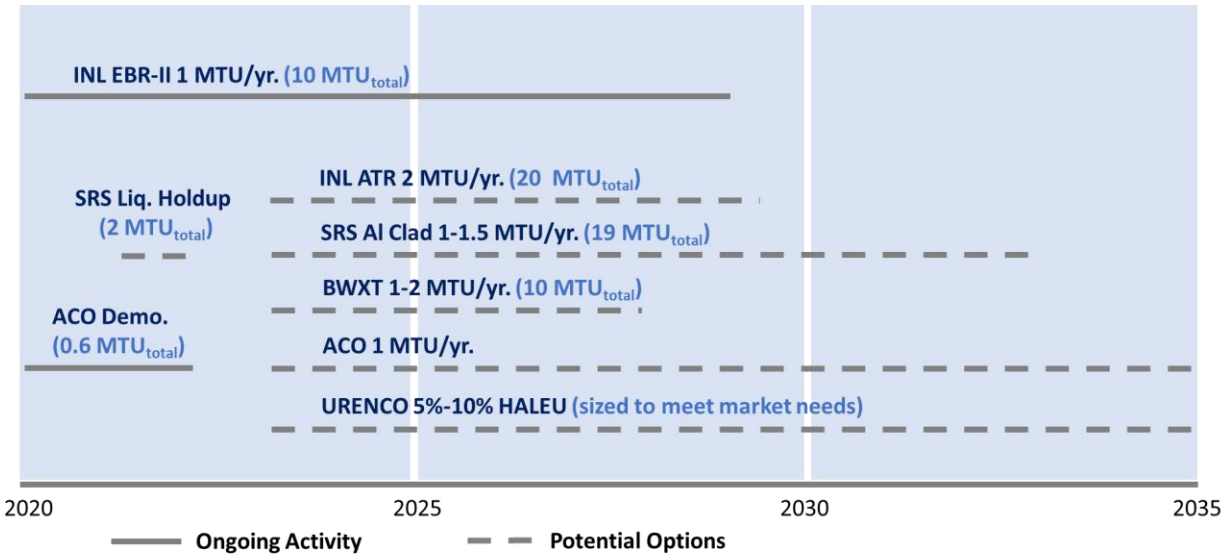

Figure 6. Approaches to support HALEU demand for early movers and initial core demands utilizing current infrastructure.

Table 2. Projected demand for HALEU in the next 10 years.

High-Fidelity Demand	Potential Commercial Demand
• Approx. 22 MTU for initial core loadings • Annual needs approx. 8-12 MTU	• 5 MTU by 2020 with a yearly exponential growth reaching 137 MTU by 2030
Assumptions Initial core loadings • DoD microreactor demonstration, DOE's advanced reactor demonstration, and DOE test and research reactors by mid-2020's Annual needs • 5 MTU DOE's advanced reactor demonstration and test and research reactors • 3-7 MTU medical isotope production and HEU to HALEU research reactor conversion (through 2033)	**Annual Forecast (NEI)** 2021 – 2.8 MTU 2022 – 3.3 MTU 2023 – 9.7 MTU 2024 – 12.0 MTU 2025 – 32.0 MTU 2026 – 64.2 MTU 2027 – 32.7 MTU 2028 – 50.0 MTU 2029 – 81.7 MTU 2030 – 137.3 MTU

Although a portion of the high-fidelity demand is currently being addressed by downblending government-owned HEU stocks, these stocks are valuable assets. If another source of HALEU existed today, these stocks would be preserved to support and extend government missions. Commercial demand for HALEU in the next 10 years could be much larger, but is more uncertain.

To accelerate development of a sustainable HALEU supply capability, an initial public/private partnership is recommended to address the high-fidelity HALEU market plus a percentage of the projected commercial demand. Given the variety of HALEU applications, the initial HALEU capability must be flexible and able to accommodate the following:

- Uranium enriched up to 10% U-235 as the feed
- Enrichments of U-235 varying from 10 to 19.75%
- Supply HALEU at a minimum annual rate of 12 MTU
- Modular design concepts to accommodate future growth
- Deconversion of UF_6 to a form (e.g., uranium oxide) suitable for production of a variety of uranium fuels forms, to include oxides, metal and alloys, and nitrides and carbides.

A pricing model that accounts for the added value of going from LEU (or LEU+) to HALEU should be established by the partnership. In addition, given the HALEU "high-fidelity" demand is mainly driven to support government agencies' projects and mission needs, a mechanism such as a lease model, wholesaler, or reserve should be developed to make HALEU available to support commercial needs.

7. FINDINGS AND RECOMMENDATIONS

Advanced reactors are being developed for flexible baseload power generation, providing US leadership in nuclear technology, enabling new markets for export, and reducing greenhouse gas emissions. Many of these reactors will require HALEU fuel which is also used for fueling research reactors and for medical isotope production facilities. There are currently no commercial suppliers of HALEU in the United States. In April 2020, the Nuclear Energy Institute (NEI), the Gateway for

Advanced Innovation in Nuclear (GAIN), and the Electric Power Research Institute (EPRI) held a virtual workshop on High-Assay Low-Enriched Uranium with the purpose of gathering a team of experts from across the national laboratories and industry to evaluate the anticipated demand for HALEU, the timing of that demand, and to evaluate the options for meeting that demand. Findings and recommendations are given below.

7.1 Findings

- Developing the HALEU fuel cycle represents an opportunity to reinvigorate domestic mining, conversion, enrichment, deconversion, and fuel fabrication in the US.
- Anticipated demand for HALEU comes from a variety of applications requiring a variety of uranium fuel forms including oxides, metal and alloys, and nitrides and carbides.
- Industry needs are the fastest growing demand for HALEU. The timing for HALEU is influenced by when and which reactor concepts mature toward commercialization.
- Relying upon market forces and demand will not be enough to create the needed HALEU fuel cycle capabilities at the time the industry will require it. Commercial investment in the front end of the fuel cycle to support HALEU production will not be made on a speculative basis.
- Transitioning from "early movers" to a "sustainable" market would be a gradual approach referred to as the "evolution" phase. The timing of when this point will be achieved is not predictable.
- The HALEU market would reach the sustainable phase when (1) a large enough customer base is evident, which will lead to securing long-term purchase agreements and (2) fuel procurement models and fuel cycle infrastructure financing tools evolve.
- Several options exist to provide HALEU in the near term for R&D and "early movers" until the market develops a commercial enrichment capability to meet long-term demands.
- Maximizing utilization of LEU (expanded to LEU+) enrichment infrastructure will significantly decrease the size of a HALEU Category II enrichment facility, resulting in lower costs and more competitive production of HALEU.
- Deconversion of HALEU enriched above 10% must also be conducted in a physical security Category II facility. Co-location of HALEU facilities (enrichment, deconversion, and fuel fabrication) with an LEU enriching facility decreases the cost of transportation and leverages security costs. Co-location of facilities will result in the most economic HALEU production model.

7.2 Recommendations

Development of future HALEU capabilities should consider all potential applications: nuclear industry, research and test reactors, and long-term applications. Near-term, predictable HALEU "high-fidelity" demand mainly supports government agencies' demonstration projects and mission needs. As such, right-sizing an initial HALEU fuel cycle infrastructure investment should be done in partnership with the government and used to support its long-term enrichment strategic mission needs. The private sector could incrementally expand the capacity in a modular fashion as a sustainable market develops.

The predictable "high-fidelity" demand of HALEU greater than 10% U-235 enriched in the next 10 years is driven by medical isotope production, HEU to HALEU research reactor conversion, the DoD microreactor demonstration, DOE's advanced reactor demonstration, and DOE test and research reactors. It is predicted that by the mid-2020's approximately 22 MTU will be needed for initial core loadings to support DoD and DOE's reactor demonstrations and DOE test and research reactors. The high-fidelity HALEU demand is estimated to be between 8-12 MTU annually for the next 10 years.

To accelerate development of a sustainable HALEU supply capability, an initial public/private partnership is recommended to address the high-fidelity HALEU market, plus a percentage of the projected commercial demand. Given the variety of HALEU applications, the initial HALEU capability must be flexible and able to accommodate the following:

- Uranium enriched up to 10% U-235 as the feed
- Enrichments of U-235 varying from 10 to 19.75%
- Supply HALEU at a minimum annual rate of 12 MTU
- Modular design concepts to accommodate future growth
- Deconversion of UF_6 to a form (e.g., uranium oxide) suitable for production of a variety of uranium fuel forms, to include oxides, metal and alloys, and nitrides and carbides.

A pricing model that accounts for the added cost of going from LEU (or LEU+) to HALEU should be established by the partnership. In addition, given HALEU "high-fidelity" demand is mainly driven to support government agencies' projects and mission needs, a mechanism such as a lease model, wholesaler, or reserve should be developed to make HALEU available to support commercial needs.