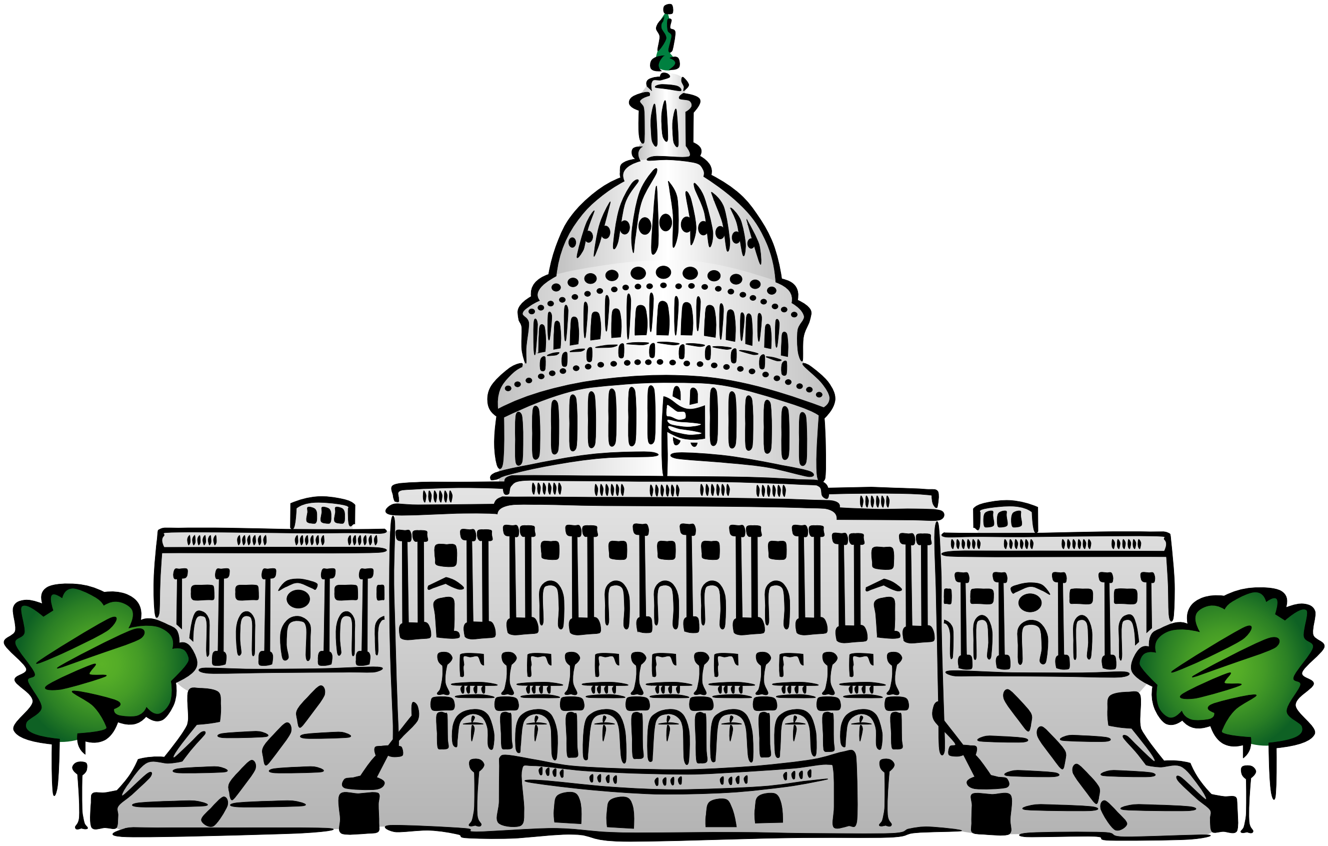

Washington Internships for Students of Engineering

Fueling the Advanced Nuclear Reactor Fleet

Sponsoring Society: American Nuclear Society

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2023

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Executive Summary

Investing in nuclear power is critical to meeting growing energy demand, achieving emissions reduction benchmarks, and maintaining international nuclear security. The United States has fostered a civilian nuclear fleet since 1958 aimed at supplying reliable baseload power to its citizens [1]. Currently, there are 93 nuclear reactors in 28 states, each using a light water reactor (LWR) design and low enriched uranium (LEU) fuel [2]. LEU used in currently operating LWRs contains up to 5 wt% uranium-235 (U-235), the main fissile isotope used to sustain a nuclear chain reaction [3]. Although the existing fleet impressively contributes 20% of electricity generation in the U.S., an emerging class of advanced reactors is projected to amplify power generation over the next several decades [2]. Advanced reactors span a wide range of designs, coolant materials, power generating size, and beyond [4]. While their definition is broad, reliance on high assay low enriched uranium (HALEU) is a common requirement of many advanced reactor designs. HALEU is fuel enriched between 5-20% U-235 [5]. The Department of Energy (DOE) predicts that the U.S. needs 40 metric tons (MT) of HALEU by 2030 to deploy an advanced reactor fleet [5].

Under the Advanced Reactor Demonstration Program (ARDP), X-Energy and TerraPower intend to demonstrate fully operational advanced reactors within the decade [6]. Originally, these nuclear companies planned on purchasing fuel from Russian state-owned Tenex, the only company in the world commercially producing HALEU [7]. With Russia's grip on 46% of global uranium enrichment capacity and its complete monopoly on commercialized HALEU production, the success of ARDP projects is inherently tied to precarious foreign relations with a U.S. adversary [8]. In February 2022, Russia invaded Ukraine, further incentivizing the U.S., European Union, and other Western nations to lessen their dependence on Russian-enriched uranium [8]. The Nuclear Fuel Security Act (NFSA) is one legislative response to this energy security threat, currently making its way through U.S. Congress [9]. This bill includes provisions to prohibit Russian uranium imports for LEU as well as to develop both LEU and HALEU domestic enrichment capabilities [9].

Supporting the HALEU fuel cycle requires bolstering production capacity across the series of chemical processing steps required to convert uranium ore to reactor fuel, including milling, conversion, enrichment, deconversion, and fuel fabrication [10]. Failure to invest in the enrichment and deconversion stages particularly would signal to advanced reactor developers that HALEU inventory cannot meet fuel loading deadlines. Simultaneously, companies with historical enrichment capacity, such as Centrus, Urenco, Global Laser Enrichment, and Orano, lack a mature market in which fully commercialized advanced reactors sign long-term purchase agreements. This "chicken-or-the-egg" conundrum could potentially delay the development of those reactors, creating a dire need for DOE to instigate a strong market signal [11].

DOE stands at a uniquely critical point to advance domestic HALEU production to power advanced reactors, specifically those under the government funded ARDP. Key policy decisions should be geared toward both addressing short-term demand for initial, within-decade HALEU required for ARDP demonstrations as well as long-term, accumulated demand for a future advanced reactor fleet. The following are policy recommendations based on key findings of domestic uranium supply chain capabilities, widespread opinions held by nuclear industry leaders, and an inventory on available uranium stockpiles:

1) **Congress should pass the Nuclear Fuel Security Act of 2023.**

The NFSA reflects the sense of Congress that the DOE should accelerate efforts to establish domestic HALEU enrichment capability on a timescale necessary to meet advanced reactor demonstration timelines [9]. Similar versions of the NFSA have been introduced in both the House and Senate of the 118th Congress. The Senate version of the bill, S. 452, would establish a Nuclear Fuel Security Program to increase the quantity of LEU and HALEU produced by U.S. nuclear energy companies and establish a HALEU for Advanced Nuclear Reactor Demonstration Projects Program to maximize potential for DOE to meet the schedules of advanced nuclear reactor developers [9]. The bill also contains provisions for LEU, including prohibiting Russian uranium imports and increasing domestic LEU enrichment capabilities [9]. The bill gives the Secretary of Energy broad authority to consider all means necessary to expedite HALEU availability, including awarding private-sector contracts and downblending government owned high enriched uranium (HEU) stockpiles [9].

2) **In the near term, DOE should make downblended uranium stockpiles available to ARDP awardees.**

There is an ongoing recycling effort for spent HEU fuel at the Idaho National Laboratory (INL) [12]. Using the Electrometallurgical Treatment Process, irradiated fuel from Experimental Breeder Reactor II is reprocessed to extract highly enriched uranium [13]. This material can then be downblended with lower-enriched (i.e., either natural or depleted) uranium to produce HALEU [14]. INL should expeditiously make available downblended HEU in HALEU form to the two demonstration reactors as quickly as possible. Also, uranium recovery and downblending efforts should be expanded to other HEU sources, including research reactors or weapons stockpiles. Feasible opportunities for downblending include the Advanced Test Reactor and the Savannah River Site [15]. Downblending HEU fuel will produce only a limited quantity of HALEU and should be used to complement a long-term, sustainable solution for domestic HALEU production.

3) **In the long term, DOE should establish a HALEU bank to develop private sector enrichment and deconversion capacity.**

DOE should establish a uranium bank as outlined under the HALEU Availability Program in the Energy Act of 2020 [16]. Under this model, DOE should support competitive, cost-shared public-private partnerships with both enrichment and deconversion companies as solicited by two requests for proposals, which have already been drafted by the Department [17]. DOE would award initial capital matched by fuel production companies to offset licensing, construction, and equipment costs required to operate commercial scale HALEU production facilities. To send strong market signals toward suppliers that there exists strong demand for HALEU, DOE would sign offtake agreements with enrichment companies for uranium hexafluoride (UF_6) and with deconversion companies for oxide and metal forms of HALEU. In both cases, the Department serves as the first buyer of fuel. DOE should sign purchase agreements with at least two suppliers each producing 10 MT of HALEU per year [15]. DOE should operate a revolving fund in which expended costs for buying HALEU would be replenished by eventual sales to advanced reactor companies, adopting a pricing model that aligns with the current fuel market. After supplying initial HALEU quantities needed for advanced reactor demonstrations, the HALEU bank would self-extinguish as the private sector adapts to the maturing supply of the advanced reactor fleet. A bank model would not only stimulate domestic HALEU production capacity, but it would also instill confidence in advanced reactor companies that their developments will meet initial projected timelines.

Forward

About the Author

Sarah Cole attends Boise State University pursuing a bachelor's degree in Materials Science and Engineering. She researches nuclear fuels in the Advanced Materials Laboratory under Dr. Brian Jaques and plans to continue her education by attending graduate school for Materials Science and Engineering. Sarah aspires to work in science and technology policy as a technical expert on nuclear materials.

About the WISE Program

The Washington Internships for Students of Engineering (WISE) Program was founded in 1980 through the collaborative efforts of several professional engineering societies to encourage engineering students to contribute to issues at the intersection of science, technology, and public policy. The nine-week Program allows fellows to spend the summer in Washington, DC, and gain exposure to the legislative and regulatory process through meetings with leaders in the Administration, federal agencies, and advocacy groups. For more information about the WISE Program, visit www.wise-intern.org.

About American Nuclear Society

The American Nuclear Society (ANS) is an international organization of scientists, engineers, and industry professionals that promote the field of nuclear engineering and related disciplines. Celebrating its 70th anniversary in 2024, ANS is the premier organization for those that embrace the nuclear sciences and technologies for their vital contributions to improving people's lives and preserving the planet. ANS is committed to advancing, fostering, and promoting the development and application of nuclear sciences and technologies to benefit society.

Acknowledgements

I would like to thank the American Nuclear Society for sponsoring me to participate in the WISE program. The experience has been truly remarkable and has shaped my perception of the importance of engineers in the public policy space. I would also like to thank Dr. Alan Levin for his guidance on my policy paper and mentorship throughout the program.

Introduction

Nuclear power is the largest source of carbon-free energy in the United States [18]. Effectively emitting no greenhouse gases during operation, the vast energetic capability of the atom has been demonstrated to reliably power a significant portion of the nation's electricity grid. In 2022, nuclear energy produced 772 billion kilowatt-hours of electricity in the U.S., amounting to 18.2% of the nation's utility-scale electricity generation[1] [19]. Not only does the nuclear industry underpin a substantial share of the nation's electricity portfolio, but it powers American homes more reliably than any electricity source with continuous, nearly uninterrupted power. Nuclear power plants operate at a 93.5% capacity factor[2], exceeding natural gas, coal, hydropower, wind, and solar [20]. While providing reliable baseload power, nuclear energy also contributes considerably to national decarbonization efforts. In fact, the existing U.S. nuclear reactor fleet prevents 500 million metric tons (MT) of carbon dioxide emissions each year [18]. Nuclear is key to achieving emissions reductions targets outlined by the Biden Administration to reduce greenhouse gas emissions by 50-52% by 2030 [21].

The current United States nuclear reactor fleet consists of 93 light-water reactors (LWR) in 28 states [2]. LWRs use ordinary water as a moderator and coolant and consist of two main types: pressurized-water reactors and boiling-water reactors [4]. The U.S. has deployed commercial nuclear reactors since 1958, yet almost all nuclear power in the U.S. derives from power plants built between 1967 and 1990 [22]. The Westinghouse AP1000 reactors at Vogtle Units 3 and 4 in Georgia are the first new nuclear reactors constructed in 30 years [2].

To continue providing reliable, clean energy, the nuclear industry is developing a fleet of advanced reactors. Compared to the current fleet, which is composed entirely of LWRs, advanced reactors employ a wide range of designs which offer "significant improvements over the most recent generation of nuclear fission reactors," as defined by the Nuclear Energy Innovation Capabilities Act of 2017 [23]. Advanced reactor designs employ a variety of coolants (i.e., water, molten salt, high temperature gas, and liquid metal), span a wide range of generating size (i.e., from several megawatts to over 1,000 megawatts), can provide additional capabilities beyond electricity (i.e., process heat for industrial purposes or clean drinking water) [23].

These technologies offer many advantages, including improved safety, decreased waste yield, and greater fuel utilization [23]. To commercialize these designs, the industry must invest heavily in high assay low enriched uranium (HALEU), the fuel used in most advanced reactors. HALEU is enriched to between 5-20% of the uranium-235 (U-235) isotope, the main fissile isotope used to sustain a nuclear chain reaction [5]. By contrast, the current LWR fleet uses low enriched uranium (LEU) with up to 5% enrichment [3]. The higher U-235 concentration allows HALEU to achieve smaller fuel assemblies and reactor designs, attain more power per unit volume, and decrease waste [5]. HALEU is key to advanced reactor deployment.

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[1] Utility-scale electricity generation is electricity generation from power plants with at least one megawatt of total electricity generating capacity.
[2] Capacity factor is defined as the ratio of actual electricity output over a given time to the theoretical maximum electrical energy output over that period.

However, the U.S. currently lacks enrichment capacity for HALEU fuel. Russia is the only nation with commercial HALEU enrichment capability, which creates inherent risk within supply chain reliability and energy security [7]. Even prior to the Russian invasion of Ukraine, leaders in the nuclear industry recognized the importance of developing a domestic uranium supply chain. In January 2022, the Nuclear Energy Institute published a report encouraging the U.S. government to “facilitate the rapid deployment of domestic HALEU enrichment production and the associated transportation and deconversion infrastructure and ensure a supply of HALEU for commercial advanced reactors” [24]. Accordingly, advanced reactor developers recognized the need to withdraw from planned commitments to Russian HALEU, sparking a demand for domestic fuel cycle capabilities.

Background

Overview of the Uranium Supply Chain

The front end of the nuclear fuel cycle is the process of converting uranium ore to reactor fuel, which requires a series of chemical processing steps. The following is an overview of the front end of the nuclear fuel cycle:

1) Mining

Uranium is mined all over the world through conventional mining and in situ recovery (ISR) [25]. Conventional mining is used to extract uranium from ore excavated in deep underground shafts or shallow open pits. ISR uses a liquid solution which leeches uranium ore from underground rock. Upon extraction, natural uranium consists of 0.7% U-235 with the remaining 99.3% containing mostly U-238 [25].

2) Milling

Uranium ore is milled to produce uranium ore concentrate (U_30_8), known conventionally as “yellowcake” [26].

3) Conversion

Yellowcake is packaged in 55-gallon drums and sent to conversion plants, where it is converted into uranium hexafluoride (UF_6) gas, cooled into a solid, then shipped to an enrichment plant [27].

4) Enrichment

Uranium is enriched to increase the U-235 concentration. While several enrichment processes exist, including gas centrifuge, gaseous diffusion, and laser separation, gas centrifuge is the process currently used for commercial enrichment [28]. This method uses a cascade of spinning gas centrifuge cylinders to separate the heavier U-238 isotopes from the lighter U-235 [28].

5) Deconversion

Deconversion is the chemical extraction of fluoride from enriched UF_6 gas to produce stable compounds of uranium as metal and oxide fuel forms. Deconversion is also performed on depleted uranium (0.2-0.3% U-235) to reduce chemical hazards associated with depleted “tails,” which exit the enrichment process as waste and are stored in large yards near enrichment facilities [29].

6) Fabrication

Fuel fabrication facilities convert enriched uranium into fuel used in reactors. To fabricate the LEU used in the current LWR fleet, enriched UF_6 is converted into a uranium dioxide (UO_2) powder, which is pressed into pellets, sintered, loaded into zirconium alloy tubes, and constructed into fuel assembly [30]. For the advanced fleet, there will be a variety of fuel types used, each of which will require its own fabrication processes.

Advanced Reactor Demonstration Timelines

To accelerate the deployment of an advanced reactor fleet, DOE launched the Advanced Reactor Demonstration Program (ARDP). ARDP has three pathways awarding competitive, cost-shared partnerships to advanced nuclear companies: Advanced Reactor Demonstrations, Risk Reduction for Future Demonstrations, and Advanced Reactor Concepts [6]. DOE awarded $160 million in initial funding under the Advanced Reactor Demonstrations pathway to TerraPower and X-energy to each demonstrate an operational advanced reactor within seven years of their award dates [31]. The Bipartisan Infrastructure Law of 2020 granted an additional $2.5 billion for the remainder of the two demonstrations [32]. DOE granted TerraPower one award to support the deployment of a fully operational 345 MWe Natrium™ sodium-cooled fast reactor with a molten salt energy storage system in Kemmerer, Wyoming [31]. The other awardee, X-energy, will demonstrate four 80 MWe small modular Xe-100 high temperature gas-cooled reactors north of Richland, Washington [31]. While the two demonstration reactors require different fabricated types of fuel (i.e., metal alloy versus TRISO[3] particles, respectively) both require HALEU. In December 2022, TerraPower announced that it must delay its planned operation date by at least two years in response to a lack of alternatives to purchase HALEU after the Russian invasion of Ukraine [33]. The absence of a domestic HALEU supply chain is problematic not only for the two demonstration projects but also for the future fleet of advanced reactors, most of which require HALEU. DOE states that over 40 metric tons of 5-20% enriched uranium are needed by 2030 with additional amounts required each year to support a fleet of advanced reactors [32].

A Deeper Dive: Sourcing Uranium

Although LEU fuel cycle infrastructure is well defined for the current nuclear reactor fleet, the U.S. lacks an established capability to fabricate HALEU on a commercial scale. Uranium mining and milling, while historically thriving American industries, currently constitute a decreased share of U.S. uranium purchases. In fact, 5% of the uranium used in the U.S. reactor fleet is mined domestically with the remaining 95% imported from foreign nations [34]. Of the 46.74 million pounds of natural uranium purchased by U.S. nuclear power plant operators in 2021, the top sources were Kazakhstan (35%), Canada (15%), Australia (14%), Russia (14%), Namibia (7%), and five other countries combined (10%) [34]. Mines are typically co-located with mills, so milling capabilities are similar.

The U.S. sources most of its converted uranium from Canada as it currently does not have its own operating conversion facilities [8]. In 2017, the Honeywell plant in Metropolis, Illinois, the last operating conversion plant, idled production in 2017 because of challenging

[3] TRISO stands for TRi-structural ISOtropic particle fuel. TRISO particles are composed of a fuel kernel encapsulated by ceramic based materials that prevent fission product release.

market conditions [35]. Otherwise, there are four conversion plants in Canada, China, France, and Russia, with Russia producing the largest share of the world's converted uranium, 38% [8].

In the U.S., domestic enrichment capabilities are limited to one commercial scale LEU facility and one demonstration scale HALEU facility. Urenco is the only company currently enriching LEU in Eunice, New Mexico [12]. Owned by the British, German, and Dutch governments, the Urenco plant has a Nuclear Regulatory Commission (NRC) license to enrich uranium up to 5.5% U-235, under the LEU+ enrichment category, which is used as more efficient fuel in the existing LWR fleet [12]. Centrus is the only facility with an NRC license to produce HALEU but does not currently yield a commercially viable amount. In 2019, DOE awarded Centrus a contract to demonstrate its AC100M centrifuge technology, extending this demonstration contract in 2022 to finish construction, complete regulatory review and licensing, and demonstrate the production of HALEU for DOE use [36].

There is only one commercial supplier of HALEU in the world, Tenex, which is owned by the Russian state-controlled nuclear corporation Rosatom [8]. With the demand for HALEU driving ARDP timeline delays, the U.S. is particularly vulnerable because of its reliance on Russian HALEU. The alternative to Russian fuel is to invest in upscaling enrichment capabilities at Centrus and Urenco to produce HALEU. Centrus stated that it could produce about 6 metric tons of HALEU per year with a full-scale 120-machine HALEU cascade within 3.5 years of securing funding [36]. However, it lacks necessary funding to do so.

The U.S. also lacks domestic deconversion capacity for HALEU. Whereas for the existing LWR reactor fleet, fuel fabricators receive UF_6 and convert it to UO_2 before fabricating it into fuel pellets and fuel assemblies, many advanced reactor designs utilize different fuel forms, such as TRISO particle, metallic, and salts. X-energy is constructing a facility to fabricate its TRISO-X fuel for its Xe-100 demonstration reactor [37]. Otherwise, the U.S. has three fuel fabrication facilities operated by Framatome, Westinghouse, and Global Nuclear Fuel to fabricate fuel pellets from enriched uranium oxide [38].

Key Findings

Ongoing Efforts to Prioritize Energy Security

The Energy Act of 2020 authorized the DOE to establish a HALEU Availability Program under the Office of Nuclear Energy, marking the first step toward securing a supply chain for advanced reactor fuel [16]. The program directed the Secretary of Energy to launch a HALEU Consortium, a committee designed to bring together stakeholders in the advanced reactor realm to inform activities related to developing a domestic HALEU supply chain. Consortium activities include providing demand estimates for HALEU, purchasing HALEU to be made available to its members, carrying out demonstration projects, and identifying opportunities to improve the HALEU supply chain [39]. Pursuant to these ambitions, the HALEU Availability Program launched a wide scale solicitation to ramp up enrichment and deconversion services for HALEU to decrease dependence on Russia. In December 2021, DOE launched a Request for Information (RFI), seeking industry feedback on the nation's projected HALEU demand [16].

Although efforts were already underway to secure a domestic HALEU supply chain, the Russian invasion of Ukraine in February 2022 made clear the need to invest expeditiously in domestic HALEU availability [40]. Nuclear utilities, already wary of a singular supplier for HALEU, realized the vulnerability of their supply chains which relied upon a foreign adversary. To establish the infrastructure needed to prioritize energy security, the DOE followed up on its RFI by publishing two Requests for Proposals (RFP) soliciting enrichment and deconversion services [17]. The enrichment RFP outlines the enrichment of UF_6 to HALEU levels, specifying that uranium used for enrichment should be mined, milled, and converted in North America, preferably in the U.S. [17]. The second RFP solicits deconversion services, including the transport of HALEU UF_6 stored at enrichment facilities to deconversion plants, deconversion of UF_6 to oxide and metal forms of HALEU, deconversion of depleted UF_6 to stable waste forms, and storage of both enriched and depleted fuel at facilities located in the continental U.S. [17].

DOE plans to enter offtake agreements with selected enrichment and deconversion companies, serving as the "first buyer" for uranium. DOE would obtain a return on investment by selling HALEU to advanced reactor utilities, establishing a supply and demand for HALEU that would accelerate a currently stagnant market. The program intends to provide confidence to advanced reactor developers that there is a reliable supply of uranium, thereby preventing further ARDP timeline delays.

The Voice of the Private Sector

The Nuclear Energy Institute (NEI) is a nuclear energy trade association representing the nuclear technologies industry. In February 2022, NEI provided feedback on DOE's initial RFI to best represent the interests of its members, which include nuclear utilities, plant designers, engineering firms, and fuel cycle companies [15]. NEI stated that the most significant barriers to establishment of a HALEU supply chain include the large upfront capital investment required to launch commercial-scale production capacity, difficulty of commercially upscaling HALEU production capacity without a sustained customer base, and a minimum four-year timeline required from procurement of funding to operational enrichment capacity [15]. To address large upfront capital costs, NEI recommended that Congress provide $200 million per year to execute the HALEU Availability Program utilizing cost-shared public-private partnerships which reduce levels of private investment [15]. In 2019, DOE signed a cost-shared partnership with Centrus Energy Corp in Piketown, Ohio to demonstrate its AC100M centrifuge cascade technology, followed by a subsequent 2022 award to demonstrate a small quantity of HALEU production [36]. The Centrus contract illustrates the need for DOE to award greater funding if commercial-scale HALEU production is to be achieved. Specifically, the projected HALEU output from the $150 million cost-shared fund is 20 kg (0.02 MT) HALEU by December 31, 2023, plus 900 kg (0.9 MT) HALEU by December 31, 2024 [36]. According to Centrus, the facility needs significant offtake agreements or additional funding to operate at a capacity of 6,000 kilograms or 6 MTU/year [36]. The NEI recommendation to invest $200 million per year would mark a significant increase in current funding initiatives and incentivize enrichment companies to establish commercial scale capacity. Government funding for initial capital costs should be supplemented by cost-shared partnerships, which reduce levels of investment by both the government and private sector, therefore lessening the risk to private investors.

Furthermore, NEI states that DOE should incentivize the deployment of multiple enrichment facilities, each with the ability to produce 10 MT of HALEU per year [15]. It is crucial that DOE invests in more than one supplier of HALEU to avoid energy security issues, such as supply chain shortages or price inflation due to supply monopoly. Multiple HALEU production sources would enable cost-competitiveness between rival companies in the distant future, maintaining a healthy fuel market. Additional demand for HALEU from outside the U.S. would furthermore support more than one supplier and alleviate some of the uncertainty associated with the magnitude of a domestic demand.

Downblending HEU Stockpiles

Given the minimum four-year timeline required for HALEU production companies to establish commercial-scale enrichment and deconversion capacity after being granted funding, NEI recommended that DOE pursue the nearer-term solution of downblending government-owned uranium stockpiles [15]. Downblending is the production of LEU by using high enriched uranium[4] (HEU) and lower-enriched (i.e., either natural or depleted) uranium [14]. HEU can be sourced from weapons stockpiles or recovered from spent nuclear fuel used in government-owned research reactors. In the case of spent research reactor fuel, HEU is obtained by recovering the uranium (which is still highly enriched, even after use in the reactor) remaining in spent HEU fuel. Recovered HEU is then combined with LEU to produce fuel enriched between 5-20% [14]. Although best suited for fast spectrum reactors (i.e., TerraPower's Natrium™ reactor) HEU recovered from spent fuel can be further processed to remove radiological and elemental contaminants for use in thermal spectrum reactors (i.e., X-energy's Xe-100 small modular reactors (SMR)) [14].

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[4] HEU is defined as uranium enriched to 20% or greater U-235.

The Electrometallurgical Treatment (EMT) Process has been used for 20 years at the Idaho National Laboratory (INL) to recover previously irradiated, sodium bonded metallic HEU fuel from Experimental Breeder Reactor II (EBR-II) [13]. Once downblended, it is estimated that this reserve can generate 10 MT of 19.75% enriched HALEU [14]. In addition, research reactor fuel from the Advanced Test Reactor could begin to be reprocessed and subsequently downblended to yield 15-20 MT of HALEU [14]. The Savannah River Site (SRS) in South Carolina is also preparing to downblend spent HEU, which is currently stored at their H Canyon facility, starting in 2025 [40].

Hybrid Zirconium Extraction (ZIRCEX) is a hybrid process that includes both recovery of HEU from spent fuel and combination of that extracted HEU with other uranium at low enrichments [41]. The HEU is recovered via solvent extraction then subsequently downblended via dissolving extracted HEU in liquid. Finally, downblended uranium is solidified to produce HALEU. ZIRCEX is currently being researched at INL using a one-fourth scale pilot facility.

Policy Recommendations

Congress should pass the Nuclear Fuel Security Act of 2023 to authorize a HALEU for Advanced Reactor Demonstration Projects Program. Meanwhile, DOE should leverage its existing legislative framework under the HALEU Availability Program to continue its solicitation of enrichment and deconversion services to establish a HALEU bank, which would send a strong market signal to advanced reactor developers. According to NEI recommendations, this program should be funded in the amount of $200 million per year. In the near-term, the Secretary of Energy should direct INL to prioritize advanced reactor demonstration projects as recipients of downblended EBR-II spent fuel and expand uranium extraction and downblending efforts to other uranium reserves.

Pass the Nuclear Fuel Security Act of 2023

In February 2023, Senators Joe Manchin (D-WV), John Barraso (R-WY), and Jim Risch (R-ID) introduced S. 452, the Nuclear Fuel Security Act (NFSA) [42]. This legislation addresses critical supply chain gaps for both LEU and HALEU sparked by the need to reduce dependence on Russian uranium. The bill supports the nation's existing nuclear fleet by prohibiting Russian imports and bolstering the domestic LEU supply chain. However, the HALEU provisions in S. 452 will be the focus of this policy recommendation.

The bill requires the Secretary of Energy to establish a Nuclear Fuel Security Program aimed at increasing the quantity of HALEU available to U.S. nuclear reactor operators [9]. The program mandates that DOE enter two or more contracts with members of the HALEU Consortium to procure 20 MT of HALEU per year by December 31, 2027. The bill specifies that DOE may only utilize uranium produced, converted, enriched, deconverted, or reduced in the U.S. or its allies. The NFSA also establishes a HALEU for Advanced Nuclear Reactor Demonstration Projects Program aimed at ensuring the availability of HALEU to meet the quantity and timeline needs of ARDP schedules until commercial capacity for enrichment and deconversion exists in the U.S. [9]. The bill asks the Secretary to consider downblending DOE stockpiles of HEU and processing uranium inventories considered excess for national security needs. Stockpiles owned by DOE would make fuel available to the HALEU Consortium with priority given to the two ARDP Demonstrations according to the following timeline: 3 MT by September 30, 2024, an additional 9 MT by December 31, 2025, and another additional 10 MT by June 30, 2026.

Passing the NFSA is imperative to meeting both short- and long-term HALEU availability goals. The legislation gives broad authority to the Secretary to consider several avenues to supply the required HALEU quantities for ARDP demonstration reactors, including downblending and soliciting private sector capabilities, while also leveraging a more diversified, long-term strategy for securing cost-shared public-private investment in the HALEU supply chain. If Congress fails to recognize the importance of ensuring HALEU quantities needed by ARDP fuel loading deadlines, then the broader advanced reactor fleet will likely suffer similar delays, withholding the vast benefits of a future advanced reactor fleet for millions of Americans.

Long-Term Solution: Establishing a Uranium Bank

While passing the NFSA would expand the Secretary of Energy's authority to act within the framework of the Nuclear Fuel Security Program, DOE is already authorized by the Energy Act of 2020 to carry out the HALEU Availability Program. This initiative establishes a framework for the DOE to solicit HALEU production services, commit to offtake agreements, and sell fuel to advanced reactors, resembling a bank.

The motivation for establishing a HALEU bank derives from informed predictions that the market for HALEU enrichment and deconversion will not develop without assistance. A 2020 report by INL indicates that although advanced reactor demonstrations will indeed create a demand for HALEU, demand would not be to an extent driving private sector investment in the HALEU fuel cycle infrastructure [14]. Enrichment companies such as Centrus, Urenco, Orano, and GLE would need long-term purchase agreements, not initial demonstration projects alone. In other words, current market forces are not strong enough to create substantial demand for HALEU fuel cycle capabilities and therefore these fuel production capacities will not arise without a strong market signal. The federal government should stimulate initial fuel cycle infrastructure investment that would spur increased private sector enrichment and deconversion capacity. As the market develops, the private sector will incrementally expand its capacity to meet growing HALEU needs of advanced reactors.

The Secretary of Energy should establish the HALEU bank as outlined in the HALEU Availability Program. DOE should expeditiously revise and publish its two draft RFPs for enrichment and deconversion services to solicit two or more contracts for each service to yield 10 MT of oxide and metal HALEU per year per vendor. Diversification of HALEU suppliers is important for establishing a culture of fuel security. The Department would then sign long term offtake agreements with fuel fabricators or reactor operators, committing to delivering enough HALEU over time to meet advanced reactor fleet requirements. DOE will own all HALEU produced and pay for fuel according to the current market value of HALEU.

Several considerations should be heeded when designing a HALEU bank. First, the bank should not compete or interfere with, but rather facilitate fuel sales among the private sector. For this reason, the bank should be designed in such a way that it could self-extinguish once initial quantities of HALEU are supplied to advanced reactors and the private market forces eradicate the need for the bank. There is limited risk to the government associated with the bank since initial costs of buying HALEU will be recovered by future sales to reactor companies. Even if initial subscribers do not make subsequent purchases, the bank, once extinguished, could sell any remaining HALEU to other advanced reactor companies or to DOE research reactors. Secondly, it is important to note that a HALEU bank is distinct from a HALEU reserve. A reserve acts as an "in case of emergency" agent to supply reserved fuel in the event of a supply chain disruption. A bank operates as a buyer and seller of HALEU to initiate strong market signals to both advanced reactor developers and fuel supply companies. It is crucial that DOE acts quickly to establish the framework for the HALEU bank model to prevent further delays in demonstrating the advanced reactor fleet.

Near-Term Solution: Downblending

Because of the minimum four-year timeline required to deploy commercial scale enrichment and conversion capacity, DOE must invest in quicker solutions for supplying HALEU to the TerraPower and X-energy demonstration reactors. INL should continue using the EMT process to extract HEU from spent research reactor fuel and downblend the recovered uranium to produce HALEU. INL should make the two demonstration reactors priority recipients of downblended fuel from this reserve, which is estimated to produce 10 MT of 19.75% enriched HALEU [13]. To fit the needs of the two demonstration reactors, INL should perform additional radiological and elemental decontamination steps prior to downblending the recovered HEU to allow for use in thermal spectrum reactors, such as X-energy's Xe-100 small modular reactors. Furthermore, SRS should expeditiously complete its preparations to reprocess HEU by its proposed 2025 timeline. INL should begin reprocessing fuel from its Advanced Test Reactor and continue researching the ZIRCEX method.

Conclusion

To ensure the success of an emerging advanced nuclear reactor fleet, Congress and the Department of Energy should make key policy decisions aimed at expediting a domestic HALEU supply chain. Congress should pass the Nuclear Fuel Security Act to give the Secretary of Energy broader authority over existing programs which could accelerate HALEU availability, continue developing a HALEU bank to send strong market signals to enrichment and deconversion companies, and direct stockpiles of HEU to be downblended and allocated toward advanced reactor demonstrations. These policy recommendations would help ensure that TerraPower and X-energy can best meet fuel loading timelines while also creating the framework for a long-term program for establishing a domestic HALEU enrichment and deconversion capacity. DOE must directly confront the “chicken-or-the-egg” scenario which could foreseeably delay advanced reactor development by instilling confidence in both fuel and reactor developers that the HALEU market will indeed come to fruition. The market will not fix itself independent of government intervention; thus, it is crucial that the U.S. invests now so that ARDP timeline targets are not delayed further. Ultimately, investing in HALEU signals a broader investment in United States nuclear energy security and welcomes the challenge to strive for global nuclear leadership.

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