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Advanced Fuels – Looming Crisis in Fueling Advanced and Innovative Nuclear Reactor Technologies

CLEARPATH

United States NIC Nuclear Infrastructure Council

White Paper on High Assay Low Enriched Uranium

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I. Introduction

Over the last five years, the United States ("U.S.") has seen the development of a series of advanced non-light water nuclear reactors ("advanced reactors") which are intended to utilize various forms of coolants and moderators that are different than the light-water cooled/moderated nuclear reactors ("LWR") that are currently deployed in the U.S. Advanced reactors utilize molten salt, high temperature gas (such as helium), lead bismuth or other materials to provide a source of cooling, moderation and heat transport. Many of these advanced reactor designs have their origin in national laboratories and most of them were first conceptualized and tested beginning in the 1950s and 1960s.

As a result of U.S. decision to deploy light-water reactors for the U.S. Navy, and subsequently for the U.S. civilian fleet, with few exceptions, virtually all of the nuclear reactors developed and built in the U.S. have been pressurized water ("PWR") or boiling water reactors ("BWR").[1] One of the advantages of this is that there is a relatively uniform, common framework for supplying materials for these reactors, including the nuclear fuel for their operation.

While the pending development of advanced reactors brings with it the potential for improved economics, lowered operating costs, higher utilization factors, enhanced safety margins and greater modularity, the fuels used to operate these reactors will be of a much greater variety in their form and composition. Additionally, many, but not all of these advanced designs, will utilize a higher enrichment of fuel than the current light water reactor ("LWR") fleet.

To fully document the potential for the advanced reactor designs, Third Way, which is a Washington, D.C. based think tank, issued a report on May 18, 2017, that indicated that there are currently 56 advanced nuclear concepts in North America under development with large numbers also underway outside the U.S.[2] From information gathered by the authors, the vast majority of these reactor designs are planning to utilize higher enrichments of fuel, and some of these designs are proposed to come to the U.S. market in the mid to late 2020s. Similarly, a March 2017 survey of 18 leading U.S.-based advanced reactors developers by the Nuclear Infrastructure Council found that 67% of the companies said that an "assured supply of High Assay LEU" was either urgent or important, with squarely 50% of the overall respondents saying it was "urgent."

As the infrastructure for the production of civilian nuclear fuel, as well as the regulatory processes overseeing its production and use, have all been based on the existing LWR market,

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[1] The exceptions include Ft. St. Vrain and Peach Bottom 1 which were high temperature gas reactors, and Fermi 1 which was a commercial fast reactor.

[2] http://www.thirdway.org/infographic/the-global-race-for-advanced-nuclear

virtually every element of the nuclear fuel cycle[3] has been tailored precisely for this market. As development and future deployment of many of the current advanced reactor designs requires utilizing fuel with higher enrichments of uranium, appropriate sources of this material will need to be identified or created, as no commercial source currently exists. This includes the means to enrich, transport, manufacture, store and dispose of this fuel.[4] The U.S. Nuclear Regulatory Commission ("NRC"), which is responsible for the regulation of all civilian uses of radioactive and nuclear material, will also need to tailor its regulatory framework to meet this need. This paper is intended to explain the current process for producing low-enriched fuel in the United States, the potential market for higher-enriched fuel that will be required by many of the advanced reactors under development, potential challenges that will be faced in supplying this higher-enriched fuel, and the regulatory changes that will be anticipated in the development of this material. The paper will also propose policy recommendations needed to accommodate the development, licensing and deployment of these reactors.

II. <u>Background on U.S. Enrichment Capabilities</u>

Uranium in nature consists of approximately 99.27% uranium 238 ("U-238") and 0.72% uranium 235 ("U-235"). In order to make it useful for power production purposes, natural uranium must be "enriched" so that the content of U-235 is increased, allowing the desired fission reaction to take place. In the U.S., LWRs utilize fuel that typically has been enriched to approximately 4.5 percent U-235 which is considered a "low-enriched fuel" ("LEU").[5]

Highly-enriched uranium ("HEU") is material that has been enriched to a level containing U-235 in a concentration of 20% or greater. HEU is a material of great concern from a security and non-proliferation standpoint because terrorists could use uranium of this enrichment to fashion a nuclear weapon. In addition to its potential use for weapons purposes, HEU is also utilized for the nuclear fleet operated by the United States Navy and for some research reactors. While the precise enrichment of naval reactor fuel is a military secret, many observers believe it ranges somewhere between 70% and 90%. Weapons grade uranium is considered material that has been enriched to a level containing U-235 in a concentration of 90% or greater.

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[3] The nuclear fuel cycle includes all the steps needed to mine, process, enrich, manufacture, use, store and permanently dispose of radioactive materials, including U-235 based fuels that are used for civilian and naval power and propulsion purposes.

[4] In parallel with the development of advanced reactor technologies, Lightbridge Corporation is developing an advanced metallic fuel design for light water reactors that has characteristics that could avoid fuel damage yet allow for increased power uprates from existing units. This fuel is designed to utilize higher enriched fuels (15-20%) and if Lightbridge is successful in getting utilities to adopt its fuel design, this could substantially increase the need for higher enrichments of uranium.

[5] There are some notable cases of plants using higher-enriched fuel. For example, Ft. St. Vrain used highly-enriched uranium (originally enriched up to 93.5%) within thorium-uranium carbide particles. *See* <u>U.S. Nuclear Waste Technical Review Board, *Department of Energy-Managed Spent Nuclear Fuel at Fort St. Vrain*</u> at 2 (2017). *See* <u>K.I. Kingrey, *Fuel Summary for Peach Bottom Unit 1 High-Temperature Gas-Cooled Reactor Cores 1 and 2*</u>, INEEL at 15-35 (2003). Fermi Unit 1 was enriched to approximately 25% U-235. *See* <u>Oak Ridge National Lab, *Integrated Data Base Report-1993: U.S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections, and Characteristics*</u>, DOE at Table A.3 (1994).

As currently conceptualized, many of the current advanced reactors under development intend to utilize high-assay low-enriched uranium ("HA-LEU") as fuel to provide greater efficiency levels than what can be achieved using the enrichment levels found in the current PWR fleet.[6] As will be described in below, this material is not commercially produced in the United States.

A. Atomic Energy Commission/DOE/ U.S. Enrichment Corporation

Beginning with the Manhattan Project during the Second World War ("WWII"), the United States utilized a process known as gaseous diffusion to enrich uranium for military and civilian purposes. The first large gaseous diffusion facility was constructed in Oak Ridge, Tennessee during WWII. Known as the "K-25 plant," this facility provided weapons grade and non-weapons grade enriched uranium to the U.S. military until it ceased operations in 1987.[7]

In 1952, the Paducah Gaseous Diffusion Plant ("Paducah") was put into operation to provide additional enrichment capabilities for the U.S. nuclear weapons program and the U.S. Navy nuclear propulsion program. Paducah was later used to supply fuel for the U.S. civilian nuclear fleet as well as for similar reactors outside of the United States, until it ceased enrichment operations in 2013. A third gaseous diffusion facility, a sister facility to Paducah, was built and operated by Atomic Energy Commission in Portsmouth, Ohio from 1954-2001 and also produced both military and civilian-use enriched materials. Under the Energy Policy Act of 1992, the U.S. Enrichment Corporation ("USEC"), a quasi-private corporation, began to operate the Portsmouth and Paducah sites in 1993.[8] At that time, USEC was the one of the largest producers of enriched uranium in the world, and was the sole U.S.-owned producer of enrichment services. After each site ceased operation—in 2013 for the Paducah site and in 2011 for the Portsmouth site—the sites was turned back to the Department of Energy for decontamination and decommissioning.

In 2014, USEC emerged from a Chapter 11 Bankruptcy Proceeding as the Centrus Energy Corporation.[9] While Centrus continues to provide enriched-uranium supply services to the civilian nuclear market, it is no longer actively enriching uranium. Rather, Centrus is now down-blending uranium obtained from the Russian nuclear weapons programs or from other non-U.S. sources. Today, there is no U.S.-owned provider of uranium enrichment services.

B. Louisiana Enrichment Services – URENCO USA

In June of 2006, URENCO USA, which is a subsidiary of URENCO,[10] received a license to construct and operate a centrifuge enrichment facility called the National Enrichment Facility ("NEF"), owned by Louisiana Enrichment Services ("LES") in Eunice, New Mexico. This facility is currently licensed to produce 5.7 million separative work units ("SWU") of uranium

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[6] HA-LEU is considered that material that has typically been enriched to between 5% and 20%.

[7] DOE, *K-25 Gaseous Diffusion Process Building*.

[8] Energy Policy Act of 1992, Pub. L. No. 102-486, 106 Stat. 2776.

[9] Centrus, *Centrus Energy Corp. Emerges from Chapter 11 Restructuring* (Sept. 9, 2014).

[10] URENCO is a European based provider of centrifuge enrichment services that is jointly owned by the governments of the United Kingdom, the Netherlands, and Germany.

per year.[11] According to URENCO USA, the NEF produced 4.7 million SWU in 2016.[12] The NEF utilizes centrifuges that were developed and manufactured in Europe by Enrichment Technology Company, Ltd., which is 50% owned by URENCO and 50% owned by Orano.[13] One of the advantages of SWU produced by centrifuge enrichment, rather than by diffusion, is that it only requires 1/10th the amount of power needed in diffusion to produce an individual SWU, which significantly reduces the cost of production.

Currently, NEF only produces LEU at levels of approximately 4.5%, but it is capable of modifying this facility to increase this level up to 19.75%.

While the plant is technically capable of undertaking this change, producing higher assay LEU at this facility would also require licensing changes. The NEF is licensed by the NRC to produce enriched uranium up to a maximum enrichment of 5%.[14] Producing uranium with a higher enrichment would require a license amendment from the NRC. LES would also need to enhance the security requirements at the site. Currently, NEF is a Category 3 facility under the NRC security definitions regarding the amount and enrichment of material that is undertaken at the site.[15] Category 3 is the lowest level of security (albeit highly robust and costly) required by the NRC in a system ranging from 1-3. Were NEF to begin enriching higher assay LEU (above 10% U-235), it would need to become a Category 2 facility, necessitating a higher level of security and a license amendment from the NRC.[16] License amendments can take several years to work their way through the NRC process.

C. Global Laser Enrichment/Silex

Beginning in the 1990s, Silex Systems Limited, based in Sydney, Australia, began to develop the Separation of Isotopes by Laser EXcitation ("SILEX") process. This process utilizes lasers to enrich uranium. In order to facilitate the potential commercial deployment of this technology in the United States, an Agreement for Cooperation between the governments of the United States and Australia was signed in May 2000.[17] In 2006, Silex signed a Technology Commercialization and License agreement with General Electric Company ("GE") to develop and commercialize the technology to enrich uranium for use in nuclear power reactors around the world. Since 2008, the project has been managed by the Global Laser Enrichment LLC ("GLE") subsidiary of GE that is owned by GE (51%), Hitachi (25%) and Cameco (24%).[18] In 2013, GLE completed

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[11] A separative work unit ("SWU"), is a standard measurement of the amount of work used to separate U-238 and U-235 in a uranium enrichment process.

[12] URENCO, *URENCO USA*.

[13] URENCO, *Enrichment Technology Company Limited*.

[14] *See* NRC, *Safety Evaluation Report for the National Enrichment Facility in Lea County, New Mexico, Louisiana Energy Services (NUREG-1827)*.

[15] Category 3 special nuclear material is enriched above natural uranium but to less than 10% U-235. *See* NRC, *Category 3 – Special Nuclear Material of Low Strategic Significance*.

[16] Category 2 special nuclear material is enriched above 10% or more U-235 but to less than 20% U-235. *See* NRC, *Category 2 – Special Nuclear Material of Moderate Strategic Significance*.

[17] SILEX, *SILEX Technology*.

[18] *Id.*

its Test Loop technology demonstration at GE's operations in Wilmington, North Carolina and received NRC commercial license approval for the technology.

On November 10, 2016, the Department of Energy announced that it had entered into contract negotiations to sell depleted uranium to GLE in order to re-enrich the material at what would be the world's first commercial laser enrichment facility. Proposed to be located in Paducah, KY, this facility would be used to re-enrich approximately 300,000 MTU of DOE tails inventories for further enrichment and use in nuclear fuel. This effort would result in approximately 100,000 MTU of natural grade uranium that would be made available for sale to the nuclear power industry over the next 40 years.[19] If built, the Silex facility would be capable of enriching uranium up to 19.75 percent.

III. The International Supply of Enrichment Services

According to the U.S. Energy Information Agency, 14 million SWU were purchased in the United States under enrichment services contracts from 12 sellers in 2016.[20] Of that 14 million SWU, the U.S.-origin share was 33% (principally from LES), and the foreign-origin SWU share was 67%. The primary foreign producers of SWU included: Russia with 22% of the total, Netherlands with 18%, Germany with 11%, and the United Kingdom with 7%.[21]

As can be seen from the table below, there are a variety of countries that currently produce uranium enrichment services. Some of these, including the U.K., France, Russia, and China are nuclear weapons states that market uranium enrichment services for export, and hence are technically capable of producing uranium in excess of the 5% level currently used in the civilian nuclear fleet. For this reason, these four countries would be considered the most likely sources of non-U.S. HA-LEU.[22] The authors have not undertaken individual contacts of all of these countries, but informally have received confirmation from sources that it is likely that each could provide such services if there were a commercial need to do so.

Table 1. International Supply of Enrichment Services

Country	***Company* and plant**	**2013**	**2015**	**2020**
France	*Areva*, Georges Besse I & II	5500	7000	7500
Germany-Netherlands-UK	*Urenco*: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK.	14,200	14,400	14,900
Japan	*JNFL*, Rokkasho	75	75	75
USA	*Urenco*, New Mexico	3500	4700	4700
Russia	*Tenex*: Angarsk, Novouralsk, Zelenogorsk, Seversk	26,000	26,578	28,663

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[19] *US DOE Sells Depleted Uranium for Laser Enrichment*, World Nuclear News (Nov. 11, 2016).

[20] EIA, *Uranium Marketing Annual Report* (Jun. 19, 2017).

[21] *Id.*

[22] While India and Pakistan are also weapons states that could, in theory, provide enrichment services in excess of 5%, we have identified no data or information indicating that either country has exported enriched uranium.

Country	*Company* and plant	2013	2015	2020
China	*CNNC,* Hanzhun & Lanzhou	2200	5760	10,700+
Other	*Various*: Argentina, Brazil, India, Pakistan, Iran	75	100	170
	Total SWU/yr approx	**51,550**	**58,600**	**66,700**

Source: World Nuclear Association *Nuclear Fuel Report* 2013 & 2015

Due to a number of policy choices and market failures, the U.S. currently has no domestically owned company that is capable of enriching uranium – at any level. While there is an overcapacity of enrichment services at the international level, not having sufficient enrichment capacity in the United States to meet domestic demand puts 20% of the U.S. power supply at risk if one or more of the sovereign-owned suppliers were to make the admittedly unlikely decision not to supply this material. Given the sensitive relations that the United States currently has with Russia and China, two large producers of enrichment, this scenario cannot be easily dismissed.

Further, the U.S. has no current domestic source of enrichment for HA-LEU, and if a U.S. company were to desire to procure materials at this level, it would currently be forced to seek such materials outside of the U.S. And, again, this sensitive procurement would need to occur with two of the four potential sources being countries with which the United States has a sensitive relationship. Additionally, as Russia and China are also trying to enter the market for advanced reactors, there is some risk that these countries might not be entirely cooperative with U.S. companies seeking HA-LEU materials.

IV. U.S. HEU/Down-blending/the Availability of HA-LEU

Beginning in 1996, as part of the "Megatons to Megawatts" program created to reduce the stockpile of U.S. and Russian nuclear weapons, DOE began a program to down-blend or convert its stockpile of HEU from former nuclear weapons into LEU for civilian nuclear fuel, making it unusable for nuclear weapons. HEU that is considered surplus is principally stored at the Y-12 Complex of the National Nuclear Security Administration ("NNSA") at a highly secure facility located at the Oak Ridge National Laboratory Site in Oak Ridge, Tennessee.[23] When ready for down-blending, these materials are shipped to a private sector facility owned by BWXT in Erwin, Tenn., or down-blended at DOE/NNSA facilities located at the Savannah River Site in Aiken, South Carolina, or at the Y-12 site.[24]

According to NNSA, approximately 186 metric tons (MT) of HEU has been slated for down blending. Of this amount, more than 143 MT have already down-blended which is equivalent to more than 5,500 nuclear weapons.[25] The remaining balance of HEU will be down-blended as additional nuclear warheads are dismantled. This material has generally been utilized for the commercial reactor fuel market or for the production of research reactor fuel.

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[23] NNSA, *U.S. HEU Disposition Program*.

[24] *Id.*

[25] *Id.*

Currently, the NNSA possesses a classified amount of HEU located at the Y-12 site for a variety of national security purposes. Of this amount, the largest share is reserved for use by the U.S. Navy Reactor Program to provide fuel for the approximately 100 nuclear reactors that propel American nuclear submarines and aircraft carriers. Using current force projections, the stockpile of HEU dedicated to this purpose, 160 metric tons of uranium, is expected to be sufficient to meet the Navy's fuel needs through 2050.[26]

Additionally, the NNSA has multi-ton stockpiles of HEU that have been reserved to meet international commitments for radioisotope production, including both targets and fuel, as well as additional fuel requirements for research reactors. Some of this material will be provided to these users at HEU levels in excess of 20% and some will be reserved to be down-blended at a level of 19.75% or less. Further, there is also a multi-ton volume of HEU that has been set aside for the space propulsion program.

Based on the most recent 2015 Secretarial Determination, there is very little HEU that is currently available to the developers of advanced reactors. There may be some very small volumes of "off-spec" or scrap HEU that could become available for modest research purposes, the volume and quality of this material is uncertain at best. As a result of meetings that the authors have had with key DOE and NNSA managers and staff, we believe that it is highly uncertain that (absent an updated Secretarial Determination freeing up additional HEU from one of the sources described above) the U.S. Government can serve as a significant or reliable source of HEU for down-blending HA-LEU. That said, there is an ongoing nuclear energy review within the Trump Administration that could address, among other things, a source of HA-LEU for the advanced reactor community.

V. Transportation Challenges

Since the development of the civilian nuclear reactor fleet in the early 1960s, with its principal focus on LEU, the production, transportation, and manufacture of higher assays of uranium, either HA-LEU or HEU, have been conducted almost entirely by or on behalf of the DOE or its predecessor the Atomic Energy Commission. With the development of advanced reactors and fuel technologies in the civilian market, there will be a variety of areas associated with the supply of this fuel that will require the time and attention of technology developers, DOE, and the NRC. One of the greatest concerns is the development and supply of sufficient fuel transport containers that can address the expected demand for these materials.

Even if Congress and the Trump Administration were able to identify appropriate domestic source(s) of HA-LEU, there remains significant challenges to transport this material in any volume due to the lack to appropriate and sufficient transport canisters. Higher assay uranium is more difficult to handle and transport due to the more complex geometric requirements needed to ensure the avoidance of accidents. As a general matter, the higher the enrichment, the smaller the volume of material that can be carried in an individual canister while avoiding criticality.

[26] DOE, *Naval Reactors*.

The possibility of a significant increase in the need for these canisters to transport higher volumes of materials enriched above 5% U-235 – based on market demands – combined with a limited number of approved canisters could create a potentially critical gap in the ability to transport sufficient quantities of these materials. New containers may need to be designed to improve shipping ability, which may also require the development of new design methods and codes. The industry may also need to develop alternative methods of transportation such as converting the uranium hexafluoride ("UF6") to an oxide or metal. In addition to the lack of sufficient transport containers for these materials, many of the potential containers may need recertification by regulatory authorities, including the U.S. Department of Transportation and the Nuclear Regulatory Commission. Licensing of these canisters can take 2 years, after the design and development work is complete. In summary, the time to take action to address this issue is short.

Outlined below are examples of some of the current container technologies.

Table 2. Sample Sizes of Cylinders for UF6 Transport[27]

Cylinder Model	**Maximum Enrichment**	**Nominal Diameter (Inches)**	**Maximum Shipping Limit (Pounds)**
Model 48Y	4.5%	48	27,560
Model 30B	5.0%	30	5,020
Model 8A	12.5%	8	255
Model 5B	100%	5	55
Model 1S	100%	1.5	1.0

While there is an insufficient amount of transport containers options for UF6, there will also need to be canisters that can transport larger volumes of uranium oxide powder and metal that is enriched beyond 4.5%. Although this paper has focused more attention to the supply of HA-LEU, we believe that the issue of transportation is potentially an equally significant issue that Congress and the Trump Administration should address in their review of matters associated with the deployment of advanced reactors.

[27] *The UF6 Manual – Good Handling Practices for Uranium Hexafluoride*, U.S. Enrichment Corporation, USEC – 651, Revision 8, January 1999, page 6.

VI. Conclusion

The development of advanced reactor technologies and advanced reactor fuels brings with it the potential for new and exciting opportunities for the U.S. nuclear industry and an opportunity to retain the historic American lead in the deployment of nuclear technologies worldwide and revitalize its nuclear fuel cycle supply chain. In the case of advanced reactors, their size, proliferation resistance, modular deployment and more cost effective designs could provide "game changing" opportunities for both domestic and international export of these technologies. However, these opportunities could be slowed or stopped because most of the advanced reactor developers in the U.S. are planning to rely on high assay low enriched uranium that is currently unavailable in the United States due an inability of the U.S. government or private industry to provide sufficient enrichment capabilities. Congress and the Trump Administration should undertake prompt action to address the lack of an adequate HA-LEU supply that could hinder the continued progress of advanced nuclear power plant deployment.

Policy Recommendations

1. Congress should direct the Secretary of Energy to establish an adequate "strategic reserve" of higher assay LEU at an enrichment of 19.75% in order to serve the needs of the advanced reactor community in the near term. The reserve should contain at least 6MT by 2020 and at least an additional 30MT by 2025.

2. Congress should direct the Secretary of Energy to develop a fast neutron test facility with a design requirement that it utilize higher assay LEU to serve as a catalyst for the early production of this material.

3. Congress should direct the Secretary of Energy to immediately declare a modest amount of its current inventory of highly enriched material, currently assigned to space or Navy propulsion needs, to be surplus in order to serve as the basis for establishing the strategic reserve outlined above.

4. Congress should direct the Secretary of Energy to conduct a study of various alternatives for minimizing the amount of HEU declared surplus under recommendation 3, including the potential to procure domestic uranium, enriched at 5% or higher to use as the feedstock for the down blending of HEU to 19.75%.

5. Congress should direct the Secretary of Energy to re-establish, within 10 years, the capability to ensure domestically enriched uranium at the level necessary to replenish the HEU materials that were declared excess in recommendation 3.

6. As an alternative to the down-blending strategy included in recommendation 3, Congress could direct the Secretary of Energy to facilitate procurement of HA-LEU in the domestic or international market.

7. Congress should direct the Secretary of Energy to determine if the current capabilities to transport HA-LEU, either in the form of UF_6, metal, oxide, or in the form of fuel for advanced reactors is sufficient to meet the expected need, and if not, shall engage in a

program with maximum reliance on the private-sector to design and seek licensing of sufficient transport containers within 5 years.

8. Congress should direct the NRC and Department of Transportation to expedite the licensing of containers for UF6, metal, oxide or other forms of advanced reactor fuels.

9. Congress should direct the NRC to expedite the process for conducting the review and approval of Category 2 security facilities.

10. Congress should direct the NRC to expedite the process for conducting the review and approval of increased enrichments of uranium.