NEI White Paper

Addressing the Challenges with Establishing the Infrastructure for the front-end of the Fuel Cycle for Advanced Reactors

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SUMMARY AND CONCLUSIONS

New reactors are urgently needed. Without them the contribution of nuclear power to the United States' energy needs will decrease over the next several decades. The vast majority of new designs require a new fuel production chain that doesn't exist today. One of the challenges associated with starting up a new industry for advanced reactors is neither the designers nor fuel producers can proceed past a certain point without the other and early in the process developers of either cannot be certain that the other is actually going to reach commercial deployment. The length of time it takes gain commercial support for funding, address technical and regulatory issues and then construct the necessary fuel cycle infrastructure creates special challenges for bringing advanced reactors to market. In order to address these challenges government coordination and support from the Department of Energy (DOE) is essential to be able to realize the benefits associated with the use of advanced reactors in the U.S.

As with bringing new advanced reactor designs to market, the fuel industry has its own hurdles. Many advanced reactors will require higher enrichments, and fuel forms very different from those manufactured for the current Light Water Reactors (LWRs). For example, the current generation of LWRs uses fuel enriched to less than 5% uranium-235. In contrast, many advanced non-LWR designs require enrichments between 5% and 20%, called High Assay Low Enriched Uranium (HALEU) fuel. In addition HALEU is also being considered for use in advanced fuels now being designed for the existing LWR fleet.

There are a number of technical and regulatory issues that need to be addressed to be able manufacture these fuels in the U.S. First there are very few, if any, criticality benchmarks for supporting the fuel cycle for higher U-235 enrichments. Despite the absence of additional benchmarks, it may be possible to design facilities and transport packages with additional conservatisms. However, this may not be a practical solution for all circumstances as the additional conservatisms will likely impact costs and operations and may not provide a commercially viable alternative. Thus developing these benchmarks is essential for developing licensing applications and approving them in an efficient, timely way. Second, certified shipping packages are needed for transport of HALEU materials. And finally updates to regulatory guidance pertaining to material control and accounting and physical security are needed to address the enrichments in the range under discussion.

Global competition is intensifying to design and build advanced reactors. Establishing HALEU fuel production capability in the near future is critical to U.S. leadership in this emerging market sector and to advancing vital strategic interests. If the United States can reclaim its historical role as the leading provider of nuclear reactors and fuel, it will be better positioned to advance nuclear safety and non-proliferation policies around the world, while ensuring a robust commercial industry domestically for decades to come. If the United States and its allies have to depend on foreign, state-owned enterprises to meet fuel needs, it will be in a much weaker position to influence these policies globally.

It is therefore imperative that the federal government and the industry work to:

- develop the fuel cycle infrastructure that will in turn allow the deployment of advanced reactors in the U.S. by the early 2030s;

- provide start-up fuel for prototype advanced reactors and test reactors by the mid-2020s; and

- support the development and deployment of advanced fuels for the current LWR fleet on an expedited basis.

Given the great potential of advanced nuclear reactors, intensity of the global competition, and the strong link to America's national interests, support of these efforts should be established as soon as possible.

To ensure that HALEU fuel is available, the industry will need:

- DOE support of:

    - Development of a new shipping package, certified for safe transport of uranium hexafluoride with enrichments from 5% to less than 20% uranium-235. In addition shipping packages will need to be designed, tested and certified for deconverted HALEU forms (e.g., oxide or metal) as well as the manufactured fuel being transported from the manufacturer to the reactor site. This effort will require cooperation and coordination between the DOE, the US Nuclear Regulatory Commission (NRC), Department of Transportation (DOT) and the industry.

    - Development of criticality benchmark data needed to license HALEU facilities and transport packages. The data should come from a federal program, developed with industry assistance.

    - Establishment of the capability to enrich uranium to between 5% and 20% uranium-235 for use in advanced LWR and non-LWR reactor fuel (i.e., design, license and construct a new facility or license and modify an existing plant).

    - Establishment of the capability to produce HALEU fuel (i.e., design, license and construct a fuel fabrication facility or modify an existing plant).

- NRC support of:
  - Finalization of the Material Control and Accountability regulatory guidance document[1] for Category II Special Nuclear Material[2] (SNM).
  - Development of guidance for implementing a Physical Security plan at a Category II SNM facility. This will require that the NRC and DOE to work together to finalize a consistent approach for addressing material attractiveness. Completing this work will enable determination of the need to continue with security rulemaking (10 CFR Part 73) and development of associated physical security guidance.
  - Collaboration with DOE and other involved parties on development of criticality benchmark data and HALEU shipping package and transporter certifications.

Financial and technical support is needed from the DOE for the development of the multiple components described above. The support is essential to establish the fuel cycle infrastructure for advanced reactors and advance LWR fuel being designed that will use HALEU. The nuclear industry is unlikely to make the financial investment when the market for advanced reactors and advanced nuclear fuel is uncertain.

As the paper will lay out in greater detail, it is anticipated that depending on the path chosen a minimum of seven to nine years would be needed to establish the commercial fuel cycle infrastructure[3] to produce both HALEU hexafluoride and the capability to manufacture HALEU fuel for advanced LWR fuels and the next generation of reactors in the United States. The scheduling timeframe in this paper presumes funding is available and is based upon estimated durations without specific project details and without full consideration of all potential parallel paths. It is intended to communicate the urgency to develop a strategy to address these issues as soon as possible to be able to establish the needed infrastructure within the next decade.

In the interim before all of these activities can be completed, the lack of supply of uranium-235 enriched to levels between 5% and 20% can be addressed by the federal government by the down-blending of HEU that could then be used to

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[1] Draft NUREG-2159, Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Special Nuclear Material of Moderate Strategic Significance.

[2] A Category II quantity of SNM material is referred to as SNM of moderate strategic significance and is 10,000 grams or more of uranium-235 enriched to 10 percent or more but less than 20 percent uranium-235.

[3] The time period is best estimate to complete all of the activities to obtain necessary criticality benchmark data, design, test and certify shipping packages, design, license and construct enrichment and fuel manufacturing infrastructure and update security requirements and guidance for Category II SNM.

manufacture HALEU fuel for prototypes and/or plant startup cores as a stop-gap measure.

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ADDRESSING THE CHALLENGES WITH ESTABLISHING THE INFRASTRUCTURE FOR THE FRONT-END OF THE FUEL CYCLE FOR ADVANCED REACTORS

INTRODUCTION

In the United States, commercial light water reactors generate electricity using low-enriched uranium (LEU) fuel. The advanced reactors being designed will also use low-enriched uranium fuel. Low-enriched uranium has uranium-235 content greater than 0.7% and less than 20%. Currently, light water reactors utilize LEU with a uranium-235 level of less than 5%. Some advanced reactors and advanced LWRs are being designed to utilize LEU with a uranium-235 level between 5% and 20%. Fuel manufactured from uranium-235 enriched to levels between 5% and 20% is referred to as High Assay Low Enriched Uranium (HALEU) fuel. These fuel designs can achieve improved fuel utilization and support better overall plant economics. With the increased interest in advanced nuclear technologies it is likely that within the next decade, both operating and newly-constructed power reactors will need HALEU fuel. To allow for the development and commercialization of these advanced reactor designs and associated fuels, the U.S. nuclear fuel cycle infrastructure must be modified to produce HALEU.

Currently there are no existing domestic facilities that make HALEU fuel on a commercial scale. Private sector fuel producers are unlikely to create such a supply absent a substantial market for HALEU fuel, e.g., a significant number of advanced fuel orders or advanced reactors under construction or firm commitments to build them. The resulting first-of a kind problem is circular; companies that need HALEU for advanced reactors or for advanced fuel for existing reactors may find it challenging to obtain until the necessary infrastructure for producing HALEU fuel is in place.

If, as anticipated, advanced non-LWR reactors do come to market within the next decade, operators may have to purchase HALEU fuel from other countries which are developing advanced reactors and the fuel cycles to support them. At that point U.S. companies will be at a disadvantage against competitors in both the domestic and export market if the U.S. cannot supply the fuel with the reactor, and do so at competitive costs. Relying on foreign suppliers for our fuel also weakens the U.S. position on both safety and nonproliferation.

U.S. jobs and global competitiveness, national security, nonproliferation, and geostrategic issues are all at stake. It is of strategic importance for the United States to develop, utilize and export reactor technology to retain the nuclear expertise and the ability to remain internationally competitive in this industry for the future. U.S. nuclear suppliers give the nation a stronger voice on nuclear safety and nonproliferation issues and the opportunity to forge long-term strategic relationships with other nations. In the absence of U.S. nuclear suppliers, other nations who are aggressively competing to win long-term supply contracts will dominate the market. Meeting this challenge will require government support for developing domestic HALEU fuel cycle infrastructure.

The primary purpose of this document is to highlight regulatory issues that need to be addressed to allow for the manufacturing and utilization of HALEU fuels in the United States. Additionally government support is needed for establishing essential pats of the infrastructure. Additional regulatory guidance is also needed to support the infrastructure development, with particular emphasis on security and safeguards.

The Atomic Energy Act of 1954 (AEA) requires a general or specific license for any person to receive, possess, use, or transfer enriched uranium, which is referred to as Special Nuclear Material (SNM).[4] The NRC regulations implementing the statutory requirements relating to SNM are set forth in 10 CFR Part 70. The provisions of Part 70 apply to all persons in the U.S. with certain clearly specified exceptions (NRC, DOE for some circumstances, DOD acting for military purposes, common carriers).[5] Specific licenses and/or specific exemptions are required to receive, possess, use or transfer SNM. Additional requirements are imposed where critical mass quantities and/or formula quantities[6] of SNM are involved; those additional requirements are dealt with in the specific license. Any planned facility to enrich uranium, including enriching from 5% to less than 20% uranium-235 or which uses, stores or transports this enriched uranium, will require a 10 CFR Part 70 license prior to being constructed. Modifying an existing facility to accommodate enrichments greater than the license allows will require an amendment to the NRC license for the facility.

SNM is separated into three categories. A Category I quantity of SNM material, which is also referred to as strategic SNM, is any SNM with uranium enriched to 20 percent or more uranium-235, uranium-233 or plutonium. A Category II quantity of SNM material is referred to as SNM of moderate strategic significance and is 10,000 grams or more of uranium-235 enriched to 10 percent or more but less than 20 percent uranium-235. Category III SNM material, also referred to as SNM of low strategic significance, is defined as 10,000 grams or more of uranium-235 contained in uranium enriched above natural but less than 10 percent uranium-235.

[4] 10 CFR Sections 70.1 and 70.2

[5] 10 CFR Sections 70.1 and 70.2.

[6] Formula quantity means strategic special nuclear material in any combination in a quantity of 5000 grams or computed by the formula, grams= (grams contained U-235) + 2.5 ((grams U-233 + grams plutonium). This class of material is sometimes referred to as a Category I quantity of material. See 10 CFR Section 70.4.

1. HALEU FUEL PRODUCTION

For an explanation of the steps common to current fuel and HALEU fuel, see Appendix 1.

2. ENRICHMENT

Most commercial nuclear power plants in use today are designed to use uranium enriched to between 3% and 5% uranium-235. Natural uranium contains 0.711% of the uranium-235 isotope by weight. Enrichment facilities increase the concentration of uranium-235 to the desired range for use.

Three commercial enrichment processes have been developed for use. They are: gaseous diffusion, gas centrifuge and laser separation. The gaseous diffusion and gas centrifuge processes use gaseous uranium hexafluoride to allow separation of the uranium isotopes. Laser separation technologies use either uranium hexafluoride or elemental uranium. There is no operational enrichment facility in the United States that can currently produce uranium enrichments of greater than 5%.

At present the only U.S. source for uranium enriched to greater than 5% would be uranium produced from down-blending government owned high enriched uranium (HEU). Potential supplies of HEU could include surplus weapons grade material, reprocessed naval reactor fuel or material from other programs. Down-blending has been conducted at the Nuclear Fuel Services (NFS) facility in Erwin, TN and at the Department of Energy's Y-12 facility at Oak Ridge TN. The NFS plant is a commercial Category I facility licensed by the NRC to use HEU. It primarily produces reactor fuel for the United States Navy. While DOE could theoretically provide a limited source of greater than 5% enriched uranium-235 through down-blending, this option is constrained by the availability of HEU. Thus, this approach could be a stop-gap strategy until HALEU is commercially available, but cannot be relied upon as a long-term fuel source.

2.1. Enrichment for National Security Requirements

While there is no legal restriction against using foreign enrichment technologies to produce HALEU fuel for commercial reactors, the U.S. government also requires enrichment capability to meet national security requirements. Under present U.S. policy and international agreements, that material must be produced using domestic technology.

In January 2017, the U.S. Department of Energy initiated a procurement process to secure a new domestic uranium enrichment capability, starting with a Request for Information (RFI). The RFI identified three discrete needs:

1. High-assay LEU for research reactors by approximately 2030, as well as for test reactors in approximately 2025 and demonstration reactors in approximately 2030;

2. LEU reactor fuel for tritium production by approximately 2038; and

3. HEU reactor fuel for naval reactors by approximately 2060.

The first of these needs, along with HALEU for use in the operating commercial reactors within the next 10-15 years, can likely be supplied through the use of downblended uranium inventories or through the utilization of enrichment facilities based on foreign technology (e.g., the URENCO facility in New Mexico). The latter two, however, must be supplied through the use of domestic enrichment technologies or technologies free of peaceful use restrictions.

In its RFI, the Department states that a future solicitation might require that the facility be located in the United States, be capable of producing enrichment levels up to 19.75% and eventually >93% uranium-235, and that "the enrichment technology, equipment, and materials must be of U.S. origin, or otherwise usable for national defense purposes."

If the Department invests in enrichment capability for its own purposes, it may be worthwhile to consider a path that jointly satisfies the HALEU needs of the commercial industry and the enrichment needs of the U.S. government, as long as the needs of both the commercial industry and the government are met within the requisite time frames.

2.2. **Gaseous Diffusion**

Gaseous diffusion enrichment was initially accomplished at gaseous diffusion plants located at Oak Ridge, Tennessee, Paducah, Kentucky and Portsmouth, Ohio. The U.S. produced substantial quantities of HEU in the 1940s through 1960s for defense and other purposes. The Paducah facility enriched to over 1%. This material was used as feed for Oak Ridge (which enriched to 4%) and to Portsmouth (which enriched to over 97% uranium-235). In the mid-1960's, the three plants shifted their focus to producing enriched uranium for civilian use in nuclear power plants. The plant at Oak Ridge shut down in 1987 and the plant at Portsmouth was shut down in 2001 and operations at the Paducah site were shut down in 2013. All three of these plants are being decommissioned, in part because their very high energy consumption made them un-competitive. It would not be economical to use this enrichment technology.

2.3. **Gas Centrifuge**

Gas centrifuge enrichment is the commercial enrichment process now in use in the United States. The gas centrifuge process relies on countercurrent gas centrifugation based on differential mass and centrifugal acceleration. Currently, the only one gas centrifuge commercial production plant is operating in the United States. Two other licenses have been granted by the NRC for the construction and operation of commercial gas centrifuge facilities. The status of these facilities is shown in Appendix 2[7]. Note that the one currently operating enrichment facility within the United States utilizes technology that is of not of U.S. origin which by treaty is excluded for use for any U.S. defense purposes. Additional details on these facilities are provided below.

In 2006, URENCO USA received a license to construct and operate the National Enrichment Facility in Eunice, N.M. This plant commenced operations in 2010 and is currently in operation. The analysis for the facility license was performed at 6% enrichment in the cascade with a limitation of 5% for withdrawal.

In 2004, the NRC licensed the United States Enrichment Corporation (USEC) to construct and operate a demonstration and test facility known as the Lead Cascade in Piketon, Ohio. The NRC also licensed USEC in 2007 to build and operate the American Centrifuge Plant (ACP) at Piketon. (USEC now operates as Centrus). The ACP is licensed to 10% enrichment in the cascade, with a condition to inform NRC 60 days prior to withdrawal of material enriched to greater than 5%. Construction of the facility is not being pursued at this time.

In 2011, the NRC issued a license to Areva Enrichment Services to construct and operate the Eagle Rock plant near Idaho Falls. The analysis for the facility license was performed at 6% enrichment in the cascade with a limitation of 5% for withdrawal. In 2017, AREVA requested that NRC terminate the license for the Eagle Rock Enrichment Facility.

2.4. **Laser Enrichment**

In the 2000s, GE, Hitachi (GEH) and Cameco entered into a business venture to develop uranium enrichment services capability. This venture, the Global Laser Enrichment (GLE) LLC made plans to commercially develop the SILEX laser isotope separation process technology under an agreement reached with Silex Systems Limited of Australia. In October 2006, GE received the required U.S. government authorizations to proceed with the technology exchange.

[7] NRC Website

GLE defined multiple phases of the project: 1) test loop operations; 2) a license for a commercial-scale enrichment plant in Wilmington, NC; and 3) agreement with the Department of Energy (DOE) to purchase high assay uranium tails for re-enrichment at a proposed Paducah Laser Enrichment Facility (PLEF), in Paducah, Kentucky. Over the past decade, GLE has advanced the technology, successfully illustrating the concept through a test loop facility. In September 2012, NRC staff issued a license to construct and operate the facility. The facility is licensed to enrich to 8% uranium-235 with notification of the NRC 60 days in advance of withdrawal of material enriched to greater than 5%. Construction of the facility is not being pursued at this time.

3. Enrichment Licensing

All of the uranium enrichment facilities now licensed to operate in the United States were licensed after the 1990 changes to the Atomic Energy Act contained in the Solar, Wind, Waste and Geothermal Power Production Act (Public Law 101-575). Any new enrichment plant, or modifications to an existing enrichment plant, falls under the new rules.

The law now requires that new enrichment facilities be licensed under the Atomic Energy Act provisions applicable to the licensing of source material and special nuclear material, rather than the provisions governing a nuclear production facility. The licensing of a facility to enrich uranium is a single step process with one license issued pursuant to 10 CFR Parts 30, 40 and 70. The licensing process for a new enrichment facility is expected to take 2 ½ years and would also require a mandatory hearing at the end which would require another ½ year to complete.

Getting regulatory approval to modify an existing license to enrich uranium to HALEU levels would be expected to take 12-18 months and require an environmental review. The most significant factor affecting the licensing of a HALEU enrichment facility – regardless of the technology used – would be the criticality safety aspects of increasing enrichment to nearly 20%. Licensing facilities for enrichment to that level would not require revisions or changes to the existing regulations. However, additional criticality benchmark data may be necessary for criticality code validation in the higher LEU enrichment range to support the establishment of reasonable safety margins (i.e., not overly conservative) in the licensing process.

4. Fabrication of HALEU Fuel

Low-enriched uranium fuel is fabricated at several U.S. facilities that sell to the commercial LWR community world-wide. There are also two U.S. facilities licensed to fabricate highly enriched fuel from existing HEU inventories, primarily for the U.S. defense industry. These two facilities have produced fuel for reactors requiring greater than 5% uranium-235 (e.g., test, medical isotope and research reactors). The higher enriched fuel is produced from HEU, which is down-blended to the needed enrichment.

Commercial reactor fuel fabrication starts with the conversion of enriched uranium hexafluoride into a form usable in reactors. U.S. LWR commercial reactor fuel production facilities convert the uranium hexafluoride to uranium dioxide and use a dry process to convert that into a uranium dioxide powder and subsequently into uranium pellets and then fuel assemblies. Manufacturing HALEU fuel for a new generation of reactors which require higher uranium-235 enrichments would likely necessitate different fuel fabrication processes (e.g., deconversion of uranium hexafluoride into uranium metal) and more conservative criticality design considerations. It should be noted that material in different forms may introduce the need to consider other safety issues related to fire protection, chemical safety and radiological controls and additional regulatory guidance may be needed in these areas.

Outside of the U.S. there are HALEU fuel production facilities that may provide criticality design information that could provide the technical basis for design of a domestic facility.

4.1. **HALEU Fuel Fabrication Licensing**

The NRC has licensed three fuel fabrication facilities that are operating now, using low-enriched uranium (i.e., less than 5% uranium-235) to produce low-enriched fuel for light water reactors. These three "Category III" facilities are the Global Nuclear Fuel Americas (Wilmington, North Carolina) the Westinghouse Columbia Fuel Fabrication Facility (Columbia, South Carolina), and the AREVA Inc., facility (Richland, Washington). These facilities would be required to obtain an extensive NRC license amendment to produce HALEU fuel. It is unclear as to whether the existing fuel facilities would be able to operate through the transition from LEU to LEU+HALEU due to the expected complexity of the plant modifications necessary to bring HALEU material within the site boundary. In addition the security requirements would be different for portions of the facility with category II and III SNM which could create additional complexity in the plant modifications.

The effort to amend these existing licenses to allow the LEU plants to process HALEU fuel would be complex and the NRC review of this type of amendment is expected to take 1 ½ years. In addition the engineering and design changes would likely require substantial redesign of the facility and likely include the construction of a new portion of the plant dedicated to the production of HALEU fuel. Therefore, it is likely that new facilities will be designed, licensed and constructed rather than amending the licenses and modifying existing facilities.

Two Category I fuel fabrication plants are currently licensed by the NRC to use high-enriched uranium: the Nuclear Fuel Services facility (Erwin, TN) and the BWXT Nuclear Operations Group plant (Lynchburg, VA). These facilities produce fuel containing both high and low-enriched uranium, for use in the U. S. Naval Reactors program. They also blend down HEU to lower enrichments, which can be used for applications such as non-power reactors[8], as well as for LEU for use in existing LWRs. With their Category I fuel facility licenses; these facilities could produce fuel for HALEU reactors. Depending on the fuel manufacturing planned, these two sites might need only minor license amendments, or none at all, to manufacture HALEU fuel.

A facility to produce HALEU reactor fuel would be licensed under 10 CFR Part 70. NUREG-1520[9] provides guidance for reviewing and evaluating the health, safety, and environmental protection impacts of applications to possess and use SNM.

10 CFR Part 70 and NUREG-1520 would apply to an application for a HALEU fuel fabrication license. There is NRC precedent for such licensing actions, in the context of both LEU and HEU fuel facilities. From a technical standpoint, there is nothing in either that would preclude their use for licensing a HALEU plant, which would be considered a Category II facility. However, new criticality benchmark data may be necessary for criticality code validation in the higher enrichment range to support the establishment of reasonable safety margin (i.e., not overly conservative) in the licensing process. Issuance of new or revised guidance for MC&A and security for Category II SNM will also pose additional challenges for licensing a HALEU facility. In order to license a Category II SNM facility the NRC needs to finalize its MC&A guidance (draft NUREG-2159) as well as make a determination on the need to conduct security rulemaking and as a minimum develop associated regulatory guidance for establishing security at a Category II SNM facility.

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[8] Non-power reactors are small reactors that do not generate electrical power but are used for research, testing, and training. Non-power reactors can include research reactors and reactors used to produce irradiated target materials.

[9] NUREG-1520, Rev. 1, “Standard Review Plan (SRP) for the Review of a License Application for a Fuel Cycle Facility.” It addresses the health, safety, and environmental protection requirements of 10 CFR Part 20 and 10 CFR Part 70 as well as the accident safety requirements reflected in 10 CFR Part 70, Subpart H, “ Additional Requirements for Certain Licensees Authorized to Possess a Critical Mass of Special Nuclear Material.”

5. Mixed Oxide Fuel

A Mixed Oxide (MOX) Fuel Fabrication Facility is under construction at the Savannah River Site in Aiken, South Carolina. The manufacturing of MOX fuel was intended to support the DOE's Surplus Plutonium Disposition Program. Under this program, DOE planned to reduce the inventory of fissile material by converting surplus plutonium into MOX fuel for use in commercial nuclear power plants. In 2005, the Commission issued the construction authorization for the MOX facility. In 2007, two years after the authorization was issued, the construction started. In 2014, the NRC issued an order extending the construction expiration date from 2015 to 2025. When completed the facility will manufacture MOX fuel for use in LWRs. The potential use of this facility is not contemplated in this paper.

6. Transportation of HALEU Materials and Fuel

Transport is an integral part of the nuclear fuel cycle. Most material used is transported several times during its progress through the fuel cycle. The principal assurance of safety in the transport of nuclear materials is the design of the packaging, which must allow for foreseeable accidents. Transporting uranium hexafluoride enriched above 5% from the enrichment facility to the HALEU fuel fabrication facility presents a challenge. Although the uranium hexafluoride feed can be transported from the conversion facility to the enrichment facility using approved cylinders, just as is done today, at the moment there is no U. S. Department of Transportation (DOT) approved, commercially viable cylinder or packages for material that is enriched to greater than 5% uranium-235. Currently, shipments of uranium hexafluoride enriched up to 5% are made in the 30B cylinder. The use of the 30B cylinder is limited to material of up to 5% enrichment. As summarized in Table 1, the 1S, 2S, 5A and 5B cylinders utilized for HEU and the 8A cylinder (licensed to 12.5%) would be too small and uneconomical to use for commercial production for HALEU even if there were a sufficient inventory of these cylinders. Table 1 provides a list of cylinders used to transport or store natural, enriched or depleted uranium in the United States.[10]

Cylinders designed to ship uranium hexafluoride are qualified under DOT regulations; see 49 CFR Part 173.420 uranium hexafluoride (fissile, fissile excepted and non-fissile). This standard applies to the packaging and shipment of any quantities greater than 0.1 kg. These requirements include the design, fabrication, inspection, testing and marking of the packages as well as the applicable Codes and Standards for manufacturing the cylinder.

[10] ANSI N14.1-2001: Packaging of Uranium Hexafluoride for Transport, Table 1 Standard UF_6 Cylinder Data

In addition to the DOT requirements, NRC requirements in 10 CFR Part 71 must be met. These provisions provide the necessary regulatory requirements to preclude an inadvertent criticality in the package.

In the United States today, the 30B cylinder is used for almost all of the commercial transportation of LEU hexafluoride. For the shipment of uranium hexafluoride enriched to less than 5% uranium-235 using the 30B cylinder NRC regulations in 10CFR 71.55 base criticality protection on the absence of a moderator. Subcriticality is maintained, both by limiting the ratio of hydrogen to fissile atoms and assuring the cylinder is a "leak-tight" container. The justification of a "leak-tight" container is based on the physical and chemical characteristics of uranium hexaflouride under transport conditions and the rigorous quality assurance used during package filling and preparation for transport. Based in these constraints, a premise of no water in-leakage into the 30B cylinder is made for each of the above analyses. NRC practice has been to certify fissile uranium hexaflouride packages (including the cylinder which is the containment vessel and a protective overpack) that are shown to be leaktight when subject to the hypothetical accident tests and to specify that the cylinder meets ANSI N14.1. For enrichments above 5%, the exception provided in 10 CFR 71.55 for uranium hexafluoride packages will no longer apply and the license application for the new package will have to address water in the containment system. The analysis will necessitate different assumptions. In addition for enrichments in the range of 8-10% and above a moderator is not needed for criticality. This will create additional engineering, design and licensing challenges. For example, new criticality benchmark data may be necessary for criticality code validation in the higher enrichment range to support the establishment of reasonable safety margins (i.e., not overly conservative) in the licensing process for the development of commercially viable packages for the transport of uranium hexafluoride enriched up to less than 20%.

The issue of designing and licensing a commercially viable package for uranium hexafluoride enriched up to 20% could potentially be resolved by converting the enriched uranium hexafluoride to metal or oxide at the enrichment facility and transporting the metal or oxide to the fabrication facility. However, commercially viable transportation packages for this material would also have to be designed and licensed for these materials. Alternatively, the enrichment and fabrication facilities could be co-located. Until there are customers for HALEU fuel, an applicant would have to initiate the development effort for new packages with no assured market. This is unlikely to occur absent some support from the DOE.

7. Criticality Issues for HALEU Facilities

A significant factor in the licensing of any HALEU facility or equipment is criticality, and there is less benchmark data for enrichments above 5 percent. Hence the need for reliance on computer software and the importance of bounding considerations becomes greater[11]. As described in NMSS-0007, an NRC guidance document;

> *"Computer codes used for criticality calculations must be benchmarked against critical experiments that represent the specific fissile materials, configurations, moderation, and neutron-poisoning conditions that represent the facility being licensed. However, it is well recognized that existing critical benchmark experiments will never precisely match these conditions. In addition, there are fewer benchmark experiments that are available at higher enrichment ranges [e.g., between 5 to 20 percent and lower-moderation (i.e., H/X, where H is hydrogen and X is fissile media)] ranges, that could be of future interest to potential applicants. Methods are needed to extend the range of applicability of current benchmark experiments via sensitivity/uncertainty (S/U) analysis techniques."*

In addition this same reference states that:

> *"NMSS has performed extensive work with Oak Ridge National Laboratory (ORNL) to further develop criticality safety computer codes [e.g., Standardized Computer Analyses for Licensing Evaluation (SCALE)] to address these challenges. The final reports for the S/U methods were published in November 1999 as Volumes 1 and 2 of NUREG/CR-6655. The reports covered the following subjects: (1) methodology for defining range of applicability, including extensions of enrichments from 5 to 11 percent; (2) test applications and results of the method; (3) test application for higher enrichments using foreign experiments; and (4) feasibility study for extending the method to multidimensional analyses, such as transport casks and reactor fuel."*

NMSS-0007 concludes that results of the test applications of the ORNL methods showed that,

> *"for simple geometries with neutron spectra that are well-moderated (high H/X), benchmark experiments at 5 percent enrichment are*

[11] Resolution of Generic Safety Issues: NMSS-0007. Criticality Benchmarks Greater than 5% Enrichment (Rev. 2) (NUREG-0933, Main Report with Supplements 1–34) December 2011.

> *applicable to calculations up to 11 percent enrichment. These test applications also showed that benchmark experiments at intermediate and higher H/X values are not applicable to calculations at very low H/X and additionally there are few benchmarks at these very low H/X values."*

Licensing a HALEU facility or transportation package for enrichments closer to 20% may be challenging due to the limited availability of applicable benchmark data. In these cases, the Oak Ridge National Laboratory (ORNL) method provides sensitivity and uncertainty information, to help designers establish adequately large margins to cover the lack of benchmark validation. NRC guidance to the NRC staff clarifies the minimum margin of subcriticality for safety relative to a license application or an amendment request under 10 CFR Part 70, Subpart H and Fuel Cycle Safety and Safeguards-Interim Staff Guidance-10, Revision 0[12]. The problem is that, particularly as enrichment is increased above 11%, a designer may be unable to apply the needed margin using this ORNL methodology and ISG-10 and still achieve the design objectives for the process in a cost effective manner.

To facilitate the development of HALEU technology, industry and regulators need to develop criticality benchmark data, to allow the safe and effective use of HALEU fuels. As a part of this effort it is important to identify the range of material forms that will potentially be needed as it will impact the experiments.

7.1. Summary of Changes Needed to Support HALEU Facilities and Use

1. A new enrichment plant could be licensed as a standalone facility or as an extension of an existing licensed plant. It took the NRC approximately two and ½ years to approve licenses submitted for facilities enriching to less than 5%, under 10 CFR Part 70 with an additional 6 months for completion of a mandatory hearing. While a HALEU facility would be more complex, the NRC should be able to issue a license in a similar time period, assuming adequate criticality benchmark data is developed. The NRC review for modifying an existing enrichment facility license to authorize increased enrichment would be expected to take twelve to eighteen months.

2. Criticality benchmark data would be needed to support the licensing of an enrichment facility producing material between 11% and 20%. Developing this data would probably take more than a year, and would need government financial support. The data could be developed by the Department of Energy or the private sector in cooperation with the NRC.

[12] USNRC, Fuel Cycle Safety and Safeguards-Interim Staff Guidance-10, Revision 0 (FCSS-ISG-10, Revision 0), ML061650370

3. Approved packages are needed for shipping HALEU hexafluoride and other materials including fresh fuel. Criticality benchmark data would also be needed to support package certification at these higher enrichments.

4. Government assistance is necessary for the industry to license and build fuel fabrication facilities that can produce HALEU fuel.

8. MATERIAL CONTROL AND ACCOUNTING (MC&A) FOR HALEU FUEL

MC&A and Physical Protection are part of the same discipline usually collectively referred to as safeguards. Safeguards are generally understood to be (1) measures taken to deter, prevent or respond to the unauthorized possession or use of significant quantities of SNM through theft or diversion and (2) measures taken to protect against radiological sabotage of nuclear activities. The goal of MC&A is to (1) maintain current knowledge of the location of SNM and resolve any discrepancies and (2) prevent undetected access resulting in unauthorized changes to values of SNM at a site that might ultimately result in diversion of SNM. MC&A also complements international treaty obligations by accounting for SNM at facilities and reporting the quantity of SNM at those facilities, as appropriate, to the International Atomic Energy Agency (IAEA). As provided by 10 CFR Part 70.22 (b) each applicant for a license to possess special nuclear material, to possess equipment capable of enriching uranium, to operate an uranium enrichment facility, to possess and use at one time and location special nuclear material in a quantity exceeding one effective kilogram[13] must provide an application which contains a full description of the applicant's program for control and accounting[14] of such special nuclear material or enrichment equipment that will be in the applicant's possession under license to show how compliance with the requirements of the applicable 10 CFR Part 74 requirements are accomplished. Nuclear material control and accounting for special nuclear material of moderate strategic significance is described in 10 CFR Part 74.41. Any commercial facility engaged in enrichment of HALEU or fabrication of HALEU fuel would be required to complete a program description for its material control and accounting.

A MC&A program is the way a facility operator conducts a sustainable, effective graded safeguards program for the control and accounting of nuclear materials, to detect and deter theft and diversion of SNM. The MC&A program implements a defense-in-depth approach to ensure that all accountable nuclear materials are in their authorized location and being used

[13] Note: one effective kilogram is defined for uranium with an enrichment in the isotope U–235 of 0.01 (1%) and above, its element weight in kilograms multiplied by the square of its enrichment expressed as a decimal weight fraction).

[14] The NRC refers to this process as the Material and Control Accounting program; DOE refers to analogous processes the Material and Control Accountability program.

for their intended purposes, such that single component failures will not result in significant vulnerabilities.

NRC licensees who are authorized to possess SNM of moderate strategic significance (Category II SNM), are required to establish, implement and maintain a Commission-approved MC&A system that will:

1. Maintain accurate, current, and reliable information on, and confirm the quantities and locations of SNM in the licensee's possession;

2. Conduct investigations and resolve any anomalies indicating a possible loss of special nuclear material;

3. Permit rapid determination of whether an actual loss of a significant quantity of SNM has occurred, with significant quantity being either:

    a. More than one formula kilogram of strategic SNM; or

    b. 10,000 grams or more of uranium-235 contained in uranium enriched up to 20.00 percent.

4. Generate information to aid in the investigation and recovery of missing SNM in the event of an actual loss.

Each applicant for a license and each licensee that, upon application for modification of its license, would become newly subject to the requirements of this section shall:

1. Submit a fundamental nuclear material control (FNMC) plan describing how the performance objectives of 10 CFR Part 74.41(a) will be achieved, and how the system capabilities required by 10 CFR Part 74.41(c) will be met; and

2. Implement the NRC-approved FNMC plan submitted pursuant to the above paragraph of this section upon the Commission's issuance or modification of a license or by the date specified in a license condition.

The FNMC plan must also address the capabilities required by 10 CFR Part 74.41(a). The MC&A system must also include the capabilities described in 10 CFR Part 74.43, that is the internal controls, the inventory and the records and the measurements and measurement controls described in 10 CFR Part 74.45 and must incorporate checks and balances to detect falsification of data and reports that could conceal unauthorized diversion of SNM.

The regulatory requirements for nuclear material control and accounting for special nuclear material of moderate strategic significance are clearly described in 10 CFR Part 74. At present there is a gap in regulatory guidance in the safeguards regime for MC&A of Category II SNM. The NRC has developed a Part 74 rulemaking to revise and consolidate the MC&A requirements in order to update, clarify, and strengthen them. The NRC intends to finalize the revised rule in 2018. Draft regulatory guidance (draft NUREG-2159[15]) has been developed along with the proposed rule that also fills the gap and provides specific guidance for facilities utilizing uranium of moderate strategic significance. Although there has been concerns raised by the industry over the need for the Part 74 rulemaking, the staff should move forward with issuance of the guidance for MC&A for Category II SNM. NRC review criteria for high-enriched uranium are published in NUREG 1280, Rev. 1. The guidance for low enriched facilities is contained in NUREG-1065.

8.1. HALEU Material Control and Accounting Summary

Until recent medical isotope production facility licensing, it has been several decades since a facility in the United States was licensed to possess special nuclear material of moderate strategic significance. Lack of experience in licensing these types of facilities introduces additional uncertainty in the licensing process, which could affect both the timeliness and economics of the licensing process.

Prior to the initiation of licensing of a facility for Category II SNM, the NRC's guidance for establishing a Category II SNM MC&A program, including the FNMC plan, needs to be finalized and issued.

9. Physical Protection of HALEU Plants and Materials

10 CFR 70.22(k) requires license applicants seeking to possess SNM of moderate strategic significance to include a physical security plan that demonstrates how the applicant will meet the requirements of 10 CFR Part 73.67(d)[16]. The plan must address how and where the material is to be stored, who may access the material, and how this access is controlled. A security organization must be described, a communication plan is required and written response procedures dealing with threats of theft of these materials must be established and maintained. NRC licensees who are authorized to possess SNM of moderate strategic significance are required to establish, implement and maintain a Commission approved Physical Security Plan that will achieve these objectives. The NRC's current policy is not to require the physical protection systems of facilities with Category II SNM to protect against a design basis threat for theft or diversion and radiological sabotage. Rather, for these facilities, the NRC's policy is to require licensees to meet a

[15] Draft NUREG-2159, Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Special Nuclear Material of Moderate Strategic Significance
[16] 10 CFR 73,"Physical Protection of Plants and Materials"

set of requirements, the effectiveness of which have been evaluated based on NRC threat assessments as well as consequence and security assessments for these facilities. The physical protection requirements are generally graded based on the risk of the material being used for malevolent purposes. The principal RGs used in licensing Category I, II and III facilities are RG 5.52, “Standard Format and Content of a Licensee Physical Protection Plan for Strategic Special Nuclear Material at Fixed Sites” (NRC, 1994); RG 5.55, “Standard Format and Content for Safeguards Contingency Plans” (NRC, 1978b); and RG 5.59, “Standard Format and Content of a Licensee Physical Protection Plan for Special Nuclear Material of Moderate or Low Strategic Significance” (NRC, 1983).

The perceived threat for theft or diversion and radiological sabotage has changed since the security requirements for Category II SNM were last updated. Changes to the threat environment were highlighted by the terrorist attacks of September 11, 2001, caused the NRC to reevaluate its security programs. In 2002 and 2003, the NRC issued orders for Interim Compensatory Measures to Category I fuel cycle facilities and for Additional Security Measures to Category III fuel cycle facilities to increase the physical protection at these facilities. Similar security orders were issued to new licensees. However, the NRC did not have a Category II SNM facility licensed in 2002 and as a result the NRC did not issue Category II facility security orders. NRC is in the process of considering revision of its regulations for physical protection of SNM. In 2014 NRC, working with Los Alamos National Laboratory, performed a material attractiveness study that analyzed SNM types and forms and their attractiveness to adversaries and recommend physical security measures to protect SNM. The results of the study were to be utilized to provide the regulatory basis for a proposed 10 CFR Part 73 rulemaking. In June of 2014 the NRC requested comment on a draft regulatory basis to support rulemaking to amend portions of 10 CFR Part 73 to strengthen physical protection of SNM at NRC-licensed facilities and in transit. One of the stated objectives of the 10 CFR Part 73 rulemaking is to risk-inform physical protection requirements against theft or diversion of SNM using a graded approach that considers material attractiveness. In 2015, NRC concluded the regulatory basis was sufficiently complete and provided adequate justification to initiate the rulemaking. Subsequently, the NRC staff commenced work on the proposed rule to update 10 CFR Part 73 and associated guidance documents. During the proposed rulemaking effort, NRC staff interacted with the DOE to ensure consistency on its material attractiveness approach. At this time, the rulemaking effort has been suspended pending review of information shared between the two Federal agencies related to material attractiveness. At this stage in the process details of the changes to the rule being contemplated are not well understood by external stakeholders.

9.1. HALEU in Transit

Performance objectives of the physical protection systems in transit are described in §73.67(a) for Category II materials. In ways similar to the fixed facility physical protection requirements, physical protection requirements for material in transit are graded based on risk. Also, it should be noted that 10 CFR 73.24, "Prohibitions," requires NRC preapproval of shipment schedules for Category II transport.

9.2. HALEU Physical Security Summary

1. The regulatory requirements for physical security of Category II SNM that apply to HALEU fuel and are described in 10 CFR 73.67. However until recent medical isotope facility applicants, no U.S. facilities have been licensed to possess special nuclear material of moderate strategic significance for several decades.

2. Over time, the perceived threat has changed and as a result the planned protective measures for Category II SNM need to be reevaluated for the current perceived threat.

The lack of recent NRC licensing introduces additional uncertainty that could affect both the timeliness and economics of the process. To limit this uncertainty, prior to the initiation of a licensing effort, the NRC should update its plans for revision of 10 CFR Part 73 and development of associated guidance documents. The guidance should cover Physical Security Plans for facilities licensed under 10 CFR 70.22(k) for SNM of moderate strategic significance and address the changed threat environment. In the interim, prior to completion of rulemaking, if needed, the NRC could establish Category II SNM security requirements through the issuance of facility specific orders. The NRC is expected to address this issue for medical isotope facilities that would be licensed to possess Category II SNM at some time during 2018.

10. Conclusions and Recommendations

- Developing the needed fuel cycle infrastructure to support the development and deployment of advanced reactors that utilize HALEU fuels will require government involvement and support by DOE and NRC in cooperation with the U.S. nuclear industry.
- The DOE and the U.S. nuclear industry, in cooperation with the NRC, should develop the necessary criticality benchmark data, to allow efficient and cost effective licensing of a new generation of HALEU fuel facilities and transportation packages. HALEU licensees will likely need this criticality benchmark data to achieve an efficient cost effective design option.

- DOE, NRC, and DOT involvement with government funding will be necessary to support the design and certification of packages and transporters that can be used to economically transport HALEU hexaflouride, HALEU in metal and oxide forms and manufactured HALEU fuels.
- The NRC working in conjunction with DOE and the U.S. nuclear industry, as well as other stakeholders, should finalize the regulatory guidance for establishing a Category II SNM MC&A program.
- The NRC in collaboration with DOE should also determine the need conduct Part 73 rulemaking and development of associated guidance for an acceptable physical security plan to facilitate the licensing of HALEU facilities. If the rulemaking is needed it should be pursued on an expedited basis.
- To maintain the viability of the U.S. nuclear industry and to ensure ongoing international competitiveness, the U.S. Government should provide assistance for the domestic industry to design, license and construct a HALEU enrichment facility and HALEU fuel fabrication facilities. A key issue that must be addressed involves first-mover barriers for U.S. companies, who will face competition from foreign state-owned enterprises. Lessons from other industries, where technologies developed in the U.S. ultimately transferred overseas, should be reviewed to identify a viable strategy for supporting a competitive U.S. domestic approach to HALEU enrichment and fuel fabrication.
- Beyond the changes being contemplated to security requirements for SNM, no additional changes to existing regulations have been identified for licensing the facilities needed to produce HALEU fuel.

11. Projected Timeline

This timeline has been developed to illustrate the sequence of events needed to support HALEU reactor fuel development. To develop a more accurate projection a more detailed project plan would be needed. The projected timeline for each portion of the effort in sequence is listed.

11.1. **Step 1 Preparation Phase**

a. Develop criticality benchmark data to facilitate design of an enrichment facility, a HALEU fuel fabrication facility and a transportation package for HALEU uranium hexafluoride and other fuel forms including metallic uranium, uranium dioxide, uranium silicide, uranium nitride and potentially uranium carbide from 11% to 19.75% uranium-235. Development of the testing program and publication of the resulting data is estimated to take approximately 1-2 years.

b. The NRC and the DOE, working together, must evaluate existing HALEU physical security requirements and the need for revision based on the change in the threat environment. This evaluation should occur in the near term to allow sufficient time to promulgate any needed changes regulatory requirements and the development of the associated regulatory guidance. This effort is projected to take 2-3 years.

11.2. Step 2 Transport Package Certification

a. Department of Energy and Department of Transportation with input from the nuclear industry will certify a nuclear industry designed package for the transport of HALEU uranium hexafluoride and other fuel forms as needed. The effort is expected to take at least 2 years and will extend until 1 year after the development of the needed criticality benchmark data.

11.3. Step 3 Design Phase

a. Design a facility for the commercial enrichment of HALEU fuel. This is expected to be done by the nuclear industry with financial assistance from the U.S. Government. Expected time to complete a design for a HALEU enrichment facility is 1-2 years. This effort cannot begin until after the completion of Step 1 (a) and cannot be completed until after the completion of Step 1 (b).

b. Design a HALEU fuel fabrication facility. This is expected to be done by the nuclear industry with financial assistance from the U. S. Government. Expected time to complete a design for a HALEU fuel fabrication facility is 2 years. This effort cannot begin until after the completion of Step 1 (a) and cannot be completed until after the completion of Step 1 (b).

11.4. Step 4 Licensing Phase

a. NRC to conduct a licensing review for HALEU enrichment facility. Expected time for licensing review is 2 ½ years. For amending an existing license to enrich up to 10% it is expected to take 1 – 1.5 years. This effort cannot begin until completion of Step 3 (a).

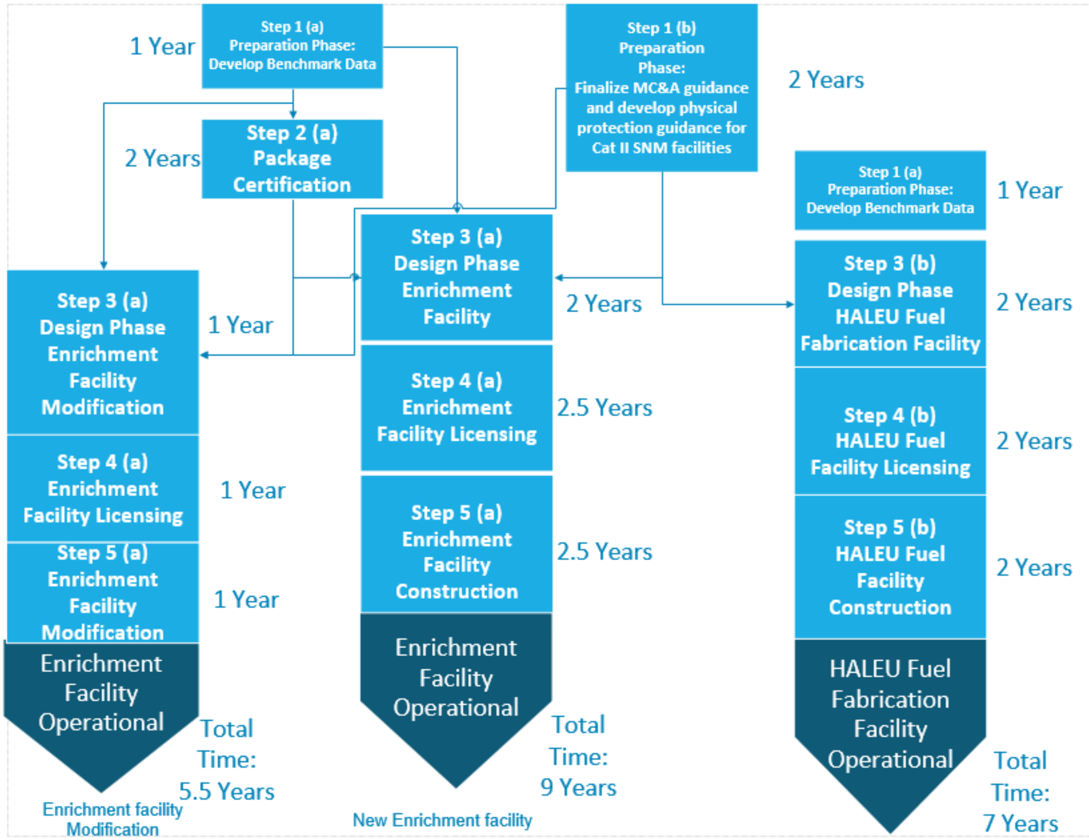
b. NRC to conduct a licensing review for HALEU fuel fabrication facility. Expected time for this review is 2 years. This effort cannot begin until after the completion of Step 3 (b) and cannot be completed until after the completion of Step 1 (b).

11.5. Step 5 Construction Phase

a. Construct the HALEU enrichment facility. Estimated time for construction is 2 ½ years. The estimated time to modify a facility to handle enrichments from 5-10% is 1 year. This effort cannot begin until after the completion of Step 4 (a).

b. Construct the HALEU fuel fabrication facility. Estimated time for construction is 2 years. This effort cannot begin until after the completion of Step 4 (b).

Figure 1: PROJECTED TIMELINE FOR ENRICHMENT AND HALEU FUEL FABRICATION



Note: Steps 3-5 for development of Enrichment capability may in part be performed in parallel to reduce the overall time. However, the overall time to complete all activities is considered as what can be reasonably achieved.

LIST OF REFERENCES

(1) 10 CFR Part 20, "Standards for Protection against Radiation"

(2) 10 CFR Part 40, Domestic Licensing of Source Material

(3) 10 CFR Part 51 Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions

(4) 10 CFR Part 70, Domestic Licensing of Special Nuclear Material

(5) 10 CFR Part 71, Packaging and Transportation of Radioactive Material

(6) 10 CFR Part 73, Physical Protection of Plants and Materials

(7) 10 CFR Part 74, Material Control and Accounting of Special Nuclear Material

(8) 10 CFR Part 75, Safeguards on Nuclear Material- Implementation of US/IAEA Agreement

(9) 49 CFR Part 173.420 - Uranium hexafluoride (fissile, fissile excepted and non-fissile

(10) Argonne National Laboratory web site. Web.ead.anl.gov/uranium/guide/uf6/index.cfm

(11) NRC Website, https://www.nrc.gov

(12) Resolution of Generic Safety Issues: NMSS-0007. Criticality Benchmarks Greater than 5% Enrichment (Rev. 2) (NUREG-0933, Main Report with Supplements 1–34) December 2011

(13) DOE-STD-1194-2011, Nuclear Materials Control and Accountability, June 2011

(14) NUREG 1520, Rev. 1, Standard Review Plan for the Review of a L:icense Application for a Fuel Cycle Facility

(15) U. S. Nuclear Regulatory staff guidance, Fuel Cycle Safety and Safeguards-Interim Staff Guidance-10, Revision 0 (FCSS-ISG-10, Revision 0), ML 061650370

(16) NUREG-1280, Rev. 1, Standard Format and Content Acceptance Criteria for the Material Control and Accounting (MC&A) Reform

Amendment, 10 CFR Part 74, Subpart E," Issued April 1995 (for high enriched uranium facilities)

(17) NUREG-1065 Rev. 2, Acceptable Standard Format and Content for the Fundamental Nuclear Material Control (FNMC) - Plan Required for Low-Enriched Uranium Facilities, Issued December 1995

(18) NUREG-1748, "Environmental Review Guidance for Licensing Actions associated with NMSS Programs, issued August 2003, provides general procedures for the environmental review of licensing actions regulated by the Office of Nuclear Material Safety and Safeguards

(19) Draft NUREG -2159 Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Special Nuclear Material of Moderate Strategic Significance

Appendix A MINING AND MILLING AND CONVERSION

The two initial steps in fuel preparation are the same for LEU fuel and HALEU fuel.

A.1. Mining and Milling

Uranium is mined throughout the world using either conventional mining techniques or "solution mining." Conventional mining includes open-pit mining and underground mining. Solution mining (also described as in-situ leaching) is becoming the dominant mining technique because it can be used to recover low grade ores that may not be economical using conventional mining techniques. Further, solution mining is generally perceived as less environmentally degrading. In solution mining, a leaching agent (acid or alkali, depending upon the properties of the formation to be mined), is injected through wells into the ore body to dissolve uranium from the ore. The leach solution is pumped from the formation and treated to recover the dissolved uranium through the use of an ion exchanger.

In either conventional mining or solution mining, after the uranium is recovered from the ore body, the concentrated uranium product is additionally refined either locally or at a uranium mill. At the mill, the uranium is converted to an oxide, which is traded commercially, and known as "yellowcake." Current world production of uranium oxide or yellowcake should easily be adequate for the production of HALEU fuels for a new generation of nuclear reactors.

The NRC licenses and regulates U.S. uranium mining and milling facilities under 10 CFR Part 40[17], or equivalent Agreement State regulations. Production of natural uranium feedstock to support the commercial HALEU fuel cycle would not require any changes to 10 CFR Part 40.

A.2. Conversion

The yellowcake is sent to a facility for conversion into pure uranium hexafluoride for use in enrichment operations. Uranium hexafluoride is the only uranium compound that exists in a gaseous state at a suitably low temperature to allow enrichment using existing mechanical isotope separation techniques. In the United States and many other countries, a dry conversion process is used to convert yellowcake to uranium hexafluoride. The dry conversion ("hydrofluor") process is used at the Honeywell plant in Metropolis, Illinois, which is the only conversion plant in the United States. In Nov 2017 Honeywell reported that there is an oversupply of uranium hexafluoride in the worldwide nuclear industry which resulted in the decision

[17] 10 CFR Sections 40.1 and 40.2.

to temporarily idle production at the Honeywell plant but it will maintain minimal operations in case business conditions improve and production at the facility can be restarted.

The dry process of uranium conversion is achieved through several steps, involving calcination, reduction, hydrofluorination, and fluorination in fluidized bed. The crude uranium hexafluoride produced in the chemical reactor is purified by fractional distillation and loaded into shipping containers for transport to an enrichment facility. The isotopic mixture of the uranium hexafluoride is the same as for natural uranium. A HALEU enrichment plant would receive uranium hexafluoride in the same shipping containers that are used today. Although the use of HALEU fuel will increase the demand for uranium hexafluoride feedstock, the increased demand is unlikely to require the need for additional mining, milling or conversion capacity in the United States. U.S. conversion facilities are also licensed under the provisions of 10 CFR Part 40. Production of natural uranium hexafluoride feedstock to support the commercial HALEU fuel cycle would not require any changes to 10 CFR Part 40.

Appendix B CURRENT STATUS OF FUEL CYCLE LICENSING ACTIVITIES FOR URANIUM ENRICHMENT FACILITIES[18]

Organization	Location	Type of Facility	Name of Facility	Status
Centrus Energy Corp.	Piketon, Ohio	Centrifuge enrichment	American Centrifuge Plant	Application submitted to the NRC in August 2004. NRC license issued in April 2007 for enrichment levels up to 10% uranium 235. No significant post-licensing construction of the American Centrifuge Plant has taken place. The Lead Cascade, a test loop for the facility, met its objectives and is now being decommissioned.
AREVA Enrichment Services	Bonneville County, Idaho	Centrifuge enrichment	Eagle Rock Enrichment Facility	Application submitted to the NRC in December 2008. License issued in October 2011. In 2017, AREVA requested that NRC terminate the license for the Eagle Rock Enrichment Facility.
Global Laser Enrichment, LLC	Wilmington, North Carolina	Laser enrichment	GLE Uranium Enrichment Facility	NRC issued a license amendment in May 2008 for a test loop. A full scale facility was licensed in September 2012, but at present it is not being built.

[18] NRC Website