



U.S. DEPARTMENT OF
ENERGY

Tritium And Enriched Uranium Management Plan Through 2060

**Report to Congress
October 2015**

**United States Department of Energy
Washington, DC 20585**

Message from the Secretary

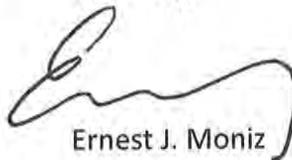
Please find the Department of Energy's plan for management of tritium and enriched uranium inventories through 2060.¹

This report is being provided to the following Members of Congress:

- **The Honorable Thad Cochran**
Chairman, Senate Committee on Appropriations
- **The Honorable Barbara Mikulski**
Ranking Member, Senate Committee on Appropriations
- **The Honorable Harold Rogers**
Chairman, House Committee on Appropriations
- **The Honorable Nita M. Lowey**
Ranking Member, House Committee on Appropriations
- **The Honorable Lamar Alexander**
Chairman, Subcommittee on Energy and Water Development
Senate Committee on Appropriations
- **The Honorable Dianne Feinstein**
Ranking Member, Subcommittee on Energy and Water Development
Senate Committee on Appropriations
- **The Honorable Mike Simpson**
Chairman, Subcommittee on Energy and Water Development
House Committee on Appropriations
- **The Honorable Marcy Kaptur**
Ranking Member, Subcommittee on Energy and Water Development
House Committee on Appropriations

If you have any questions or need additional information, please contact me or Mr. Brad Crowell, Assistant Secretary for Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,



Ernest J. Moniz

¹ In response to Title III, Division D, Section 311 of the Consolidated Appropriations Act, 2014 (Pub. L. 113-76), and other Congressional language listed in Appendix B

Executive Summary

The Department of Energy's National Nuclear Security Administration (DOE/NNSA) is responsible for a number of national missions that require a reliable supply of Enriched Uranium (EU) to meet our defense and non-defense related missions. This report summarizes plans and options for managing tritium and EU resources to satisfy U.S. national security demand through 2060 and offers analyses of demand and supply scenarios, material use restrictions, production capabilities, and production technologies needed to meet future demand along with associated cost estimates.

DOE's defense and non-defense related mission EU demands are:

Defense-Related Missions

- Highly enriched uranium (HEU) to maintain the nuclear weapons stockpile
- HEU for naval propulsion programs (powering aircraft carriers and submarines)
- HEU in support of Mutual Defense Agreements
- Low-enriched uranium (LEU) to support production of tritium

Non-Defense National Priorities

- HEU to fuel research reactors for medical isotope production and other research applications (e.g., prior to conversion to LEU fuel)
- HEU for future National Aeronautics and Space Administration (NASA) programs, power systems, and other research purposes
- Higher-assay LEU (greater than 5% and less than 20% ²³⁵U) to fuel research reactors for medical isotope production and research applications

Most of these requirements are supplied from the United States' HEU stockpile. The U.S. ceased enriching uranium for use in nuclear weapons in 1964 and stopped all HEU production in 1992. The stockpile includes HEU in weapons and components, working inventory, material in secure storage, unusable HEU in spent nuclear fuel (SNF), or other forms that are difficult and/or costly to recover. To meet the diverse needs listed above, the Department is repurposing or down-blending HEU from dismantled weapons that were declared excess to defense needs by the President in 1994 and 2005. This report outlines the Department's plans and options for managing the diminishing HEU stockpile to continue to meet those needs in the future.

U.S. nuclear nonproliferation policy and U.S. international agreements for peaceful uses of nuclear materials require that any nuclear weapons material be produced using resources, technologies, production equipment, and infrastructure that are free of peaceful use restrictions. These restrictions come from two sources: (1) foreign imposed peaceful use obligations derived from foreign-origin uranium, processing equipment, or technologies, and (2) peaceful use encumbrances derived from U.S. Government policy. These restrictions affect all conversion, enrichment, fuel fabrication, and commercial power reactors being employed for defense purposes.

The most pressing defense mission need is for tritium, which is produced by irradiating tritium-producing burnable absorber rods (TPBARs) in a single commercial light water reactor owned and operated by the Tennessee Valley Authority (TVA). The Department expects to need to use two TVA reactors to produce tritium based on recent analyses. In keeping with the above principle, each LEU fuel core loaded into TVA reactors for tritium production must consist entirely of LEU that is both free from foreign peaceful-use obligations and unencumbered by U.S. nuclear nonproliferation policy restrictions.

Previously, unobligated LEU fuel for tritium production was projected to be expended by 2027. However, DOE/NNSA has evaluated multiple options and identified three short-term actions that could extend the unobligated LEU fuel need date for tritium production from 2027 to 2038-2041. This report also outlines additional options that could potentially extend that timeline further. The methods of obtaining additional unobligated LEU and the associated cost, schedule, and risks are detailed in this report.

This report also presents an assessment of methods and technologies other than using TVA to produce tritium. It reaffirms that the DOE/NNSA agreement with TVA provides the most reliable source of tritium while minimizing consumption of unobligated EU.

Other defense and non-defense mission requirements are also addressed in this report. Of note, new sources of fuel for naval reactors will be needed in approximately 2060 and HEU inventories currently used to meet non-defense national priority missions, as currently defined, may be exhausted in approximately 10 to 15 years.

To meet mission requirements in the future, six uranium enrichment technologies that could be used to produce unobligated EU were evaluated against a standard set of criteria. Rough order-of-magnitude cost estimates are also provided.

Ensuring a long-term continuous supply of unobligated EU for defense and non-defense national priority missions will require a dedicated effort that spans multiple programs. DOE/NNSA's Office of Nuclear Material Integration coordinated the development of this plan with significant input from the Offices of Defense Programs, Defense Nuclear Nonproliferation, Naval Reactors, Nuclear Energy, and Environmental Management.



TRITIUM AND ENRICHED URANIUM MANAGEMENT PLAN THROUGH 2060

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Abbreviations

AFS	American Assured Fuel Supply
APT	Accelerator Production of Tritium Program
ATR	Advanced Test Reactor
AVLIS	Atomic Vapor Laser Isotope Separation
CLWR	Commercial Light Water Reactor
CSA	Canned Subassembly
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DP	Defense Programs
DUEP	Depleted Uranium Enrichment Project
EMIS	Electromagnetic Isotope Separation
ENW	Energy Northwest
EOT	Excess Other
EU	Enriched Uranium
HEU	Highly Enriched Uranium
INL	Idaho National Laboratory
LEP	Life Extension Program
LEU	Low-Enriched Uranium
MDA	Mutual Defense Agreement
MOX	Mixed Oxide
MTU	Metric Tons
NASA	National Aeronautics and Space Administration
NNSA	National Nuclear Security Administration
NR	Naval Reactors
NRC	Nuclear Regulatory Commission
NU	Natural Uranium
NWS	Nuclear Weapons Stockpile
PGDP	Paducah Gaseous Diffusion Plant
PPD	Presidential Policy Directive
REU	Repurposed Excess Uranium
RPD	Requirements and Planning Document
SILEX	Separation of Isotopes by Laser Excitation
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
SRS	Savannah River Site
SWU	Separative Work Unit
TPBAR	Tritium-Producing Burnable Absorber Rod
TRL	Technology Readiness Level
TVA	Tennessee Valley Authority
U.K.	United Kingdom
UIWG	Uranium Inventory Working Group
USEC	United States Enrichment Corporation (now Centrus Energy Corp.)
VHEU	Very Highly Enriched Uranium
Y-12	Y-12 National Security Complex

I. Legislative Language

The production of this report was initiated by Section 311 of Title III, Division D, of the Consolidated Appropriations Act, 2014 (Pub. L. 113-76), which states:

“(a) Not later than June 30, 2014, the Secretary shall submit to the Committees on Appropriations of the House of Representatives and the Senate a tritium and enriched uranium management plan that provides-

(1) an assessment of the national security demand for tritium and low and highly enriched uranium through 2060;

(2) a description of the Department of Energy’s plan to provide adequate amounts of tritium and enriched uranium for national security purposes through 2060; and

(3) an analysis of planned and alternative technologies which are available to meet the supply needs for tritium and enriched uranium for national security purposes, including weapons dismantlement and down-blending.

(b) the analysis provided by (a)(3) shall include a detailed estimate of the near- and long-term costs to the Department of Energy should the Tennessee Valley Authority no longer be a viable tritium supplier.”

In addition, Section 312(b) of Title III, Division D, of the Consolidated and Further Continuing Appropriations Act, 2015 (Pub. L. 113-235), requires that:

“(b) The Department shall provide a report to the Committees on Appropriations of the House of Representatives and the Senate not later than April 30, 2015 that includes:

- an accounting of the current and future availability of low-enriched uranium, highly-enriched uranium, and tritium to meet defense needs; and*
- a cost-benefit analysis of each of the options available to supply enriched uranium for defense purposes, including a preliminary cost and schedule estimate to build a national security train.”*

Finally, House Report 113-486 as incorporated in the Joint Explanatory Statement for the Energy and Water Development Appropriations Act, Title III, Division D of the Consolidated and Further Continuing Appropriations Act, 2015, states that:

The Committee will consider further investments in domestic enriched uranium capabilities only after the Secretary of Energy and the Secretary of Defense conduct a bottoms-up interagency reevaluation of the active and reserve tritium stockpile requirements, and the Nuclear Weapons Council certifies to the Committees on Appropriations of the House of Representative and the Senate that the revalidated tritium stockpile amounts to be maintained by the Department of Energy represent the minimum active and reserve national security requirements. To ensure that the results of such analysis are available for consideration of the fiscal year 2016 budget request, the Nuclear Weapons Council should provide this certification to the Committees not later than March 1, 2015.

All legislative language requirements are listed in Appendix B.

II. Introduction

The Department of Energy's National Nuclear Security Administration (DOE/NNSA) is responsible for a number of national missions that require a reliable supply of enriched uranium (EU) in varying assays and chemical forms. The missions creating this demand are:

Defense-Related Missions

- Highly enriched uranium (HEU) to maintain the nuclear weapons stockpile
- HEU for naval propulsion programs (powering aircraft carriers and submarines)
- HEU in support of Mutual Defense Agreements
- Low-enriched uranium (LEU) to support production of tritium

Non-Defense National Priorities

- HEU to fuel research reactors for medical isotope production and other research applications (e.g., prior to conversion to LEU fuel)
- HEU for future National Aeronautics and Space Administration (NASA) programs, power systems, and other research purposes
- Higher-assay LEU (above five and less than 20 percent ²³⁵U) to fuel research reactors for medical isotope production and research applications

Most of these requirements are supplied from the U.S. HEU stockpile. The United States ceased enriching uranium for use in nuclear weapons in 1964 and stopped all HEU production in 1992 (Figure 1). None of the U.S. Government facilities built to produce this inventory remain in operation.

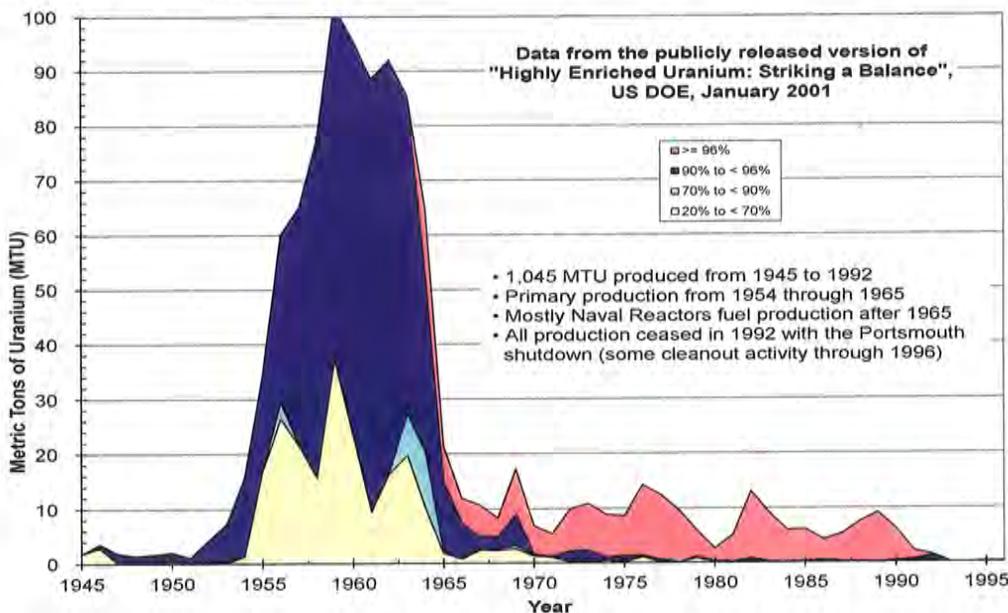


Figure 1. History of U.S. HEU Production. Material produced between 1964 and 1992 was predominantly for U. S. Navy nuclear propulsion applications

The United States produced more than 1000 metric tons (MTU) of HEU before stopping production in 1992 and by September 30, 1996, had 741 MTU of HEU in inventory.² This included HEU in weapons and weapon components, working inventory, and material in secure storage. The inventory also included unusable HEU contained within spent nuclear fuel (SNF) or other forms that are difficult and/or costly to recover. The President, in 1995, declared 174.3 MTU of HEU excess to U.S. defense needs (the S94 declaration, based on a National Security Council review begun in 1994).³ The President's Declaration was made with the intent of eliminating the possibility of using this material for nuclear explosive use or other military (including naval propulsion) application.⁴ In keeping with this intent, DOE/NNSA has down-blended much of this original excess HEU for use as LEU and research reactor fuel consistent with the Declaration's policy.

LEU derived from the HEU declared excess by the S94 Declaration is encumbered and is not available for national security purposes, including tritium production. In a second declaration made in 2005 (the E05 declaration), the Secretary of Energy committed an additional 200 MTU of HEU to be permanently withdrawn over time from use in nuclear warheads.⁵ However, the E05 Declaration specifically allocated 160 MTU for naval propulsion use, with the remaining 40 MTU earmarked to support other programs uses, such as use as fuel for space and research reactors, and for down-blending to LEU. Any material rejected by the Navy would be redirected to these uses as well. Figure 2 shows the excess uranium inventories and the restrictions on them.

² January 2001, Highly Enriched Uranium: Striking a Balance, Revision 1

³ This amount was later increased to 175 MTU.

⁴ March 1, 1995, President Clinton Speech; February 6, 1996; Secretary O'Leary Openness Initiative Announcement; and, July 29, 1996, U.S. Department of Energy Record of Decision for the Disposition of Surplus Highly Enriched Uranium Final Environmental Impact Statement.

⁵ October 24, 2005 Memorandum from Linton F. Brooks, NNSA Administrator: "Secretary's Security Initiative for Highly Enriched Uranium (HEU)."

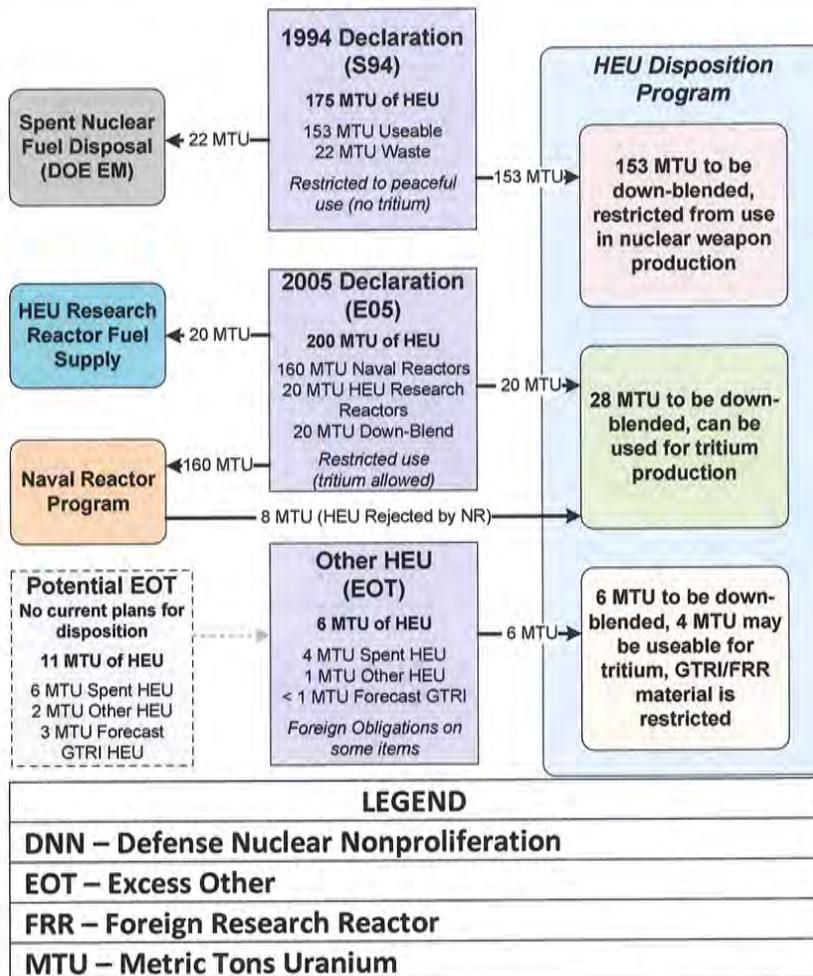


Figure 2. DOE Excess HEU Inventories for Down-Blending

As weapons stockpile inventories continue to be drawn down, the Department is repurposing or down-blending HEU from dismantled weapons to comply with the two declarations. All U.S. and foreign demand associated with LEU fuel and targets used for research reactors, isotope production, and nonproliferation initiatives is met by down-blending U.S. HEU declared excess by one of these declarations.^{6,7,8}

Over the last two decades, DOE has been actively down-blending HEU from the S94 and E05 excess material declarations through the HEU Disposition Program. These down-blending programs have produced fuel for U.S. commercial power plants and for research reactors in the United States and around the world. To date, more than 146 MTU of the excess material has been down-blended. Roughly 40 MTU of useable excess HEU remains available to down-blend.

⁶ For LEU assays above 5 percent ²³⁵U.

⁷ ~19.75 percent ²³⁵U.

⁸ e.g., conversion of HEU-fueled research reactors to 19.75 percent LEU.

This report outlines the Department's plans for managing the diminishing stockpile of HEU to meet the diverse needs listed above for as long as possible, as well as options for continuing to meet those needs in the future.

The Department is providing this document to summarize its plans and options for managing tritium and enriched uranium (EU) resources to satisfy U.S. national security demand through 2060. This document offers analyses of demand and supply scenarios, material use restrictions, production capabilities, production technologies, and cost estimates needed to meet future demand and presents potential actions to ensure an adequate supply of tritium and EU in support of national security objectives. This document also provides an assessment of alternatives for the Department should the Tennessee Valley Authority (TVA) no longer be a viable supplier of irradiation services to support tritium production.

III. National Security Demand for Tritium and Unobligated LEU for Tritium Production

U.S. nuclear deterrent systems require reservoirs filled with tritium (^3H) gas. To ensure active systems have the required amount of tritium, DOE/NNSA must maintain an inventory adequate to supply these systems, a working inventory, and a presidentially mandated reserve. These three requirements are laid out in U.S. nuclear weapons stockpile (NWS) Presidential Policy Directives (PPDs) and subordinate implementing documents.⁹

Tritium Demand

Tritium, although naturally occurring in minute quantities, must be manufactured to produce the quantities needed for National Security purposes. Maintaining the required supply of tritium is challenged by the fact that tritium radioactively decays to helium-3 (^3He) at a rate of 5.5 percent per year. Thus, after 12.3 years, one-half of the DOE/NNSA tritium inventory is lost to decay.

Tritium reservoirs from inactive weapons and aged reservoirs in active weapons are removed and sent to the Savannah River Site (SRS) tritium facility where the gas is removed, separated from its decay products, and returned to inventory. Because some tritium is lost to natural radioactive decay, replenishment through production is vital to ensuring that an adequate supply of tritium is available to support national security requirements. Annual tritium production schedules are developed and adjusted based on assessments of available inventory, recycle and recovery, supply infrastructure, reserves, and other factors to ensure tritium requirements continue to be met.

The Nuclear Weapons Council (NWC) directs the development of the Requirements and Planning Document (RPD), which defines stockpile quantities, based on PPDs and other related documents. Drawing on the RPD, DOE/NNSA defines its Plan of Record for weapons components, including tritium fill weights.

DOE/NNSA is responsible for defining tritium fill weights for each weapon system in order to meet the military's performance characteristics for the entire lifecycle of the weapon. These fill weights depend on the military requirements for weapon yields and the analysis of available test data to ensure that weapon performance over a range of environmental conditions will meet requirements.

The overall tritium demand requirements are subdivided into the follow categories:

- Facility infrastructure (Required Minimum Inventory) at SRS;
- Active stockpile (with associated tritium fills);

⁹ Program requirement documents flow from Presidential Policy Directive 9 (PPD-9), Fiscal Years 2011-2017 Nuclear Weapons Stockpile Plan (U) dated July 15, 2011, and subordinate planning documents approved by the Nuclear Weapons Council.

- Laboratory research, development, and surveillance;
- System pipeline (transit of weapon's Gas Transfer Systems to and from DOD deployment sites and SRS);
- Hedge and reserve (tritium required to reactivate weapons or protect against a production outage); and,
- Presidentially mandated strategic reserves.

In fiscal year (FY) 2015, DOE/NNSA, along with the national laboratories and responsible operating contractors, conducted a detailed review of the tritium inventory and requirements. Variables that drive the quantities in these categories include tritium fills and the stockpile which consists of its size, types of warheads, and the readiness states. These variables were reviewed against the best planning information to date and the sensitivity these variables have on future tritium demand. The net result was a projected tritium production requirement at its peak of 2800 grams per 18-month cycle.

The results of the review were presented to the Nuclear Weapons Council Standing and Safety Committee (NWCSSC) Action Officers, the NWCSSC, and the NWC. The information was used in their process for certifying the tritium production requirements and thus issuing an NWC certification letter. Classified Appendix D discusses these variables, or demand drivers, in more detail.

Tritium Production

Tritium for the nuclear weapons program is currently produced by irradiating lithium aluminate ceramic pellets contained within tritium-producing burnable absorber rods (TPBARs) with high-energy neutrons in commercial light water reactors (CLWRs) owned and operated by TVA. As shown in Figure 3, the irradiated TPBARs are sent to the NNSA Tritium Extraction Facility at SRS to remove the tritium from irradiated TPBARs and package it for use. The first NNSA extraction of tritium from TVA's CLWR-irradiated TPBARs was successfully completed at the SRS Tritium Extraction Facility in January 2007.

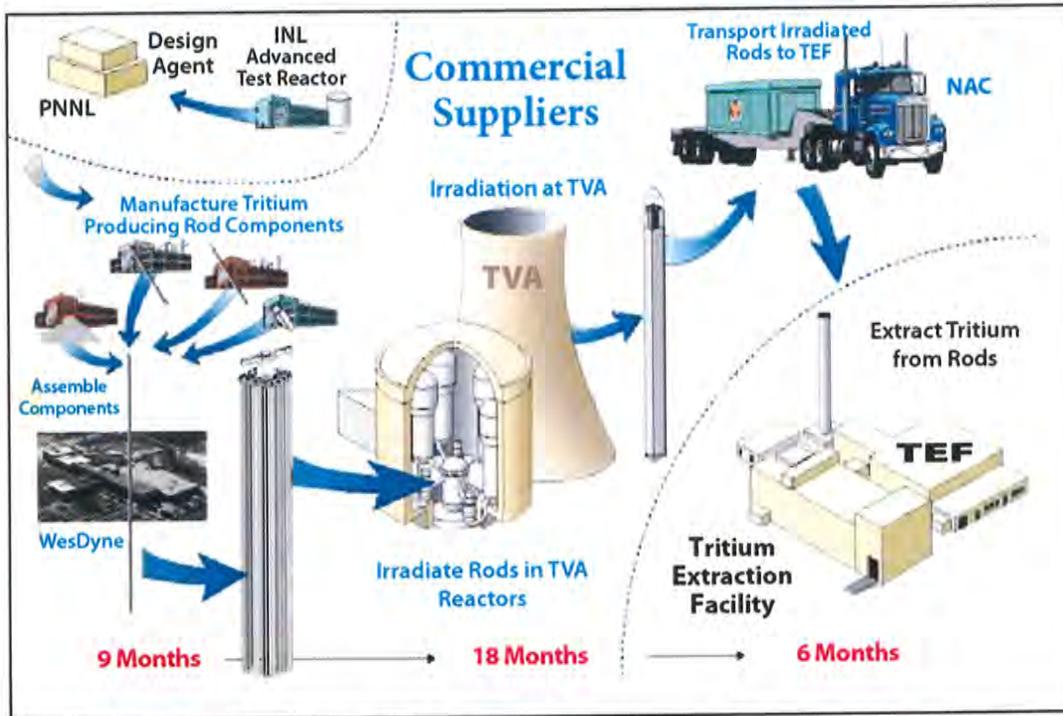


Figure 3. Current NNSA Tritium Production Process

Tritium currently is produced in just one reactor—Watts Bar Unit 1 (WBN1). DOE/NNSA’s current projections require significantly increasing production to meet tritium requirements. To inform its future decisions to meet these increased requirements, DOE/NNSA has undertaken a Supplemental Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor (CLWR SEIS) pursuant to the National Environmental Policy Act.¹⁰ While the draft CLWR SEIS issued in August 2014 identified DOE/NNSA’s preferred alternative as continuing to use only Watts Bar 1, the Department has continued to assess its tritium requirements and now expects to need to use two TVA reactors to produce tritium. Use of the second reactor would likely begin in the early 2020s. This alternative was analyzed as Alternative 6 in the CLWR SEIS and the Final CLWR SEIS expected to be issued later this year.

The two-reactor plan is considered the most reliable scenario to ensure adequate tritium production to meet the demand as it mitigates both operational and production risks and increases the likelihood that tritium requirements will be met. Under the two reactor plan, potential variations in demand can be handled with relatively small changes in fresh fuel requirements.¹¹ This alternative could increase TPBAR loading in the existing reactor to TVA’s

¹⁰ This document supplements the 1999 *Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor* (DOE/EIS-2088).

¹¹ TPBARs can only be inserted into fresh fuel. If two reactors are used, the amount of fresh fuel needed to irradiate TPBARs would be closer to the normal amount of fuel replaced during a refueling outage, i.e. one-third of

recommended maximum level in FY 2019 and add a second reactor in the mid-2020s. DOE/NNSA analyzed this outer limit of irradiating no more than a total of 5,000 TPBARs between both reactors and believes that it will need fewer TPBARs to meet currently foreseeable requirements. Tritium production will remain at the maximum level in both reactors until an adequate tritium inventory is attained, at which time the loading may be reduced slightly in each reactor.

Unobligated LEU Fuel Requirements for Tritium Production

U.S. nuclear nonproliferation policy and U.S. international agreements for peaceful uses of nuclear materials require that any nuclear weapons materials be produced using materials, technologies, production equipment, and infrastructure that are free of peaceful use restrictions. These restrictions come from two sources: (1) foreign imposed peaceful use obligations derived from use of foreign-origin uranium, processing equipment, or technologies; and (2) peaceful use encumbrances derived from U.S. Government.

Under the current interpretation of these restrictions, all conversion, enrichment, fuel fabrication, and commercial power reactors being employed for defense purposes must be free of such restrictions. Currently, each LEU fuel core loaded into TVA reactors for tritium production consists entirely of LEU that is both free from foreign peaceful-use obligations and unencumbered by U.S. nuclear nonproliferation policy restrictions.¹²

Figure 4 shows the production and processing pathway involved in supplying unobligated uranium to the tritium production program from the commercial market. The potential to introduce peaceful use obligations must be considered at each stage of the fuel cycle as shown in the figure and is a significant challenge to the tritium production program.



Figure 4. Commercial Production of LEU Fuel

The demand for unobligated LEU reactor fuel required for tritium production is a function of the number of reactors used and, to a lesser extent, the total number of TPBARs to be

the core. If once-burned fuel can be used again, i.e. burned a second and third time, the unobligated fuel is used much more efficiently. If one reactor, in this two reactor scenario, was loaded with the maximum number of TPBARs, more fresh fuel would replace fuel that had only been burned once or twice. Allowing fuel to be burned at least three times maximizes the use of unobligated fuel. Variations in TPBAR loading that do not require additional fresh fuel assemblies and that allow fuel to be burned three times would be considered small or inconsequential.

¹² The U.S. interagency is reviewing alternatives to peaceful use obligations as it applies to tritium production.

irradiated. Increasing the number of TPBARs irradiated in a single reactor requires higher-enrichment LEU fuel. This increases both the amount of unobligated feed required and the Separative Work Units (SWU) needed from a domestic uranium enrichment source.

DOE/NNSA's current expectation for tritium production is to implement a two-reactor alternative approach, and DOE/NNSA is currently contemplating, subject to completion of applicable review under the National Environmental Policy Act and issuance of a Record of Decision, increasing the TPBAR loading in the Watts Bar 1 reactor to 1504 beginning in FY 2019 and to add a second reactor in the early 2020s. The second reactor will require two reloads (of approximately 1/3 of a core each) of unobligated uranium before any TPBARs are inserted (to ensure that no obligated uranium remains in the reactor when tritium production begins) and then gradually increase the TPBAR loading on each reload, reaching 1504 TPBARs in approximately 2025.¹³ Under such a scenario, tritium production would remain at 1504 TPBARs in both reactors until an adequate tritium inventory is attained, at which time the loading may be reduced in each reactor.

Existing Supply of Unobligated LEU for Tritium Production

The Tritium Readiness Program Baseline (Tritium Readiness Subprogram Tritium Production Fuel Supply Plan) identified three sources of unobligated fuel for tritium production through 2027 assuming a second reactor comes online in the mid-2020s.¹⁴ The first source of fuel comes from prior LEU purchases from the United States Enrichment Corporation (USEC) (now called Centrus Energy Corporation). Most of this material has already been used, with just one-half of a reactor reload remaining. The second source is the Depleted Uranium Enrichment Project (DUEP), which will provide 10 reloads. The third source provides four reloads through obligation exchanges with the Mixed Oxide (MOX) LEU Backup Inventory Project.

USEC Purchases

TVA and USEC entered into a uranium enrichment services agreement on December 30, 1999, that was originally intended to supply unobligated material to TVA's tritium program reactors for the duration of the tritium program. When USEC decided to terminate enrichment operations in June 2012, this contract was amended to be a fixed-quantity contract where only certain deliveries would be unobligated material. The final delivery of unobligated LEU under this contract occurred on October 1, 2014, from material that USEC had already produced at the Paducah Gaseous Diffusion Plant (PGDP) prior to its shutdown. The last of this LEU—about 20 MTU, or one-half of a reactor reload—is expected to be loaded into a TVA reactor in the Fall of 2015.

¹³ Reactors replace approximately one-third of their reactor fuel during each refueling outage. In order to have a completely unobligated reactor core, the previous two reactor reloads must use unobligated fuel. The third reactor reload would contain the TPBARs (see Figure 5, noting the 2nd reactor cleanout notation).

¹⁴ U.S. Department of Energy, *Tritium Readiness Subprogram Tritium Production Fuel Supply Plan*, U.S. Department of Energy, May 2014

Depleted Uranium Enrichment Project (DUEP)

DUEP was initiated in June 2012 to employ PGDP to re-enrich high-assay, depleted uranium tails to produce unobligated enriched uranium through May 2013. DUEP was a series of interrelated transactions whereby the Department transferred depleted uranium hexafluoride¹⁵ (DUF₆) to Energy Northwest (ENW), which in turn contracted with USEC for enrichment of the DUF₆. The project produced approximately 482 MTU of LEU, enriched to approximately 4.4 percent. ENW retained 47 MTU of the resultant LEU and, according to a contract with TVA, will deliver the remaining 435 MTU as LEU fuel. This is enough unobligated LEU for over 10 individual reactor reloads and will keep the TVA reactors fueled until 2024. DOE/NNSA reimburses TVA for the cost differential (the difference between the market price of LEU and the higher price paid for the unobligated LEU) for this fuel in accordance with its tritium production agreement with TVA.

MOX Backup LEU Inventory

DOE/NNSA down-blended 17.1 MTU of unobligated HEU to establish an inventory of LEU that could provide public utilities with replacement fuel if DOE/NNSA is unable to deliver MOX fuel on schedule. This action was taken to provide assurance to potential MOX customers and to mitigate the potential liability associated with an extension of a refueling outage caused by a utility having to procure additional LEU fuel before a refueling outage to replace MOX fuel were DOE/NNSA unable to deliver. The cost of down-blending the HEU was covered by allowing the down-blender to retain approximately 40 percent of the LEU produced as compensation for performing the down-blending and providing the natural uranium (NU) diluent. Most of the LEU delivered to DOE/NNSA from these transactions is unobligated LEU (173 MTU) and can be used for obligation exchanges (flags) with obligated uranium purchased by TVA on the open market for tritium production. DOE/NNSA does not plan to use the Backup Inventory itself but instead it will be used for obligation exchanges. Obligation exchanges made using this MOX Backup LEU inventory are expected to provide four reloads in the early to mid-2020s.

DOE/NNSA must exchange the obligations before the LEU has to be provided by the MOX Fuel Project or any other transfer of the material. If this inventory is needed for MOX fuel replacement before TVA needs it for tritium production, DOE/NNSA might access some other inventories of obligated LEU to make obligation exchanges, and arrange for short-term storage until it is needed by TVA for tritium production. This agreement is documented in a memorandum between the respective DOE/NNSA offices.

The baseline sources of unobligated LEU are shown in Table 1.

¹⁵ The unobligated DUF₆ averaged 0.43 percent ²³⁵U, which is well below the natural uranium level of 0.711 percent but still high enough to be economically re-enriched.

Table 1. Baseline Sources of Unobligated Uranium (Existing Sources)

Project	Available Material	Single Reactor Reloads	Extends Tritium Production Until	Relative Cost to DOE	Risk
Existing USEC LEU	20 MTU at 4.4%	0.5	2015	Low	Minimal—Already owned
ENW from DUEP	435 MTU at 4.4%	10	2024	Low	Minimal—Under contract
MOX Backup LEU Inventory	173 MTU at 4.95%	4	2027	Low	Low—DOE owned, must exchange obligations

Options for Obtaining Unobligated LEU for Tritium Production

DOE/NNSA formed a Uranium Inventory Working Group (UIWG), composed of representatives from DOE/NNSA offices and sites, to coordinate information and decisions related to the Department's uranium inventory. The UIWG's first task was to identify material that could be used to provide unobligated fuel for tritium production reactors. The UIWG worked with TVA and elements within DOE/NNSA to identify five options that each provides a few years' worth of LEU fuel for tritium production. By combining existing LEU and HEU fuel sources with some or all of these options and with the required funding, tritium production can be maintained until a long-term solution is funded, built, and placed in operation.

Option 1. Preserve Existing Unobligated LEU Inventories

Three groups of material have been identified as candidates under Option 1: preserve the obligation-free status of ENW portion of DUEP LEU; preserve unobligated Westinghouse fuel flags; and, utilize the TVA reserves.

To use these inventories, agreements must be made with the companies that own the unobligated LEU to exchange the obligations in a manner similar to that used for the DOE inventories. In addition, the Department must make arrangements, for example by contracting through TVA, for these companies to preserve the unobligated status of LEU reserves until the Department can use them in tritium reactors.

ENW Unobligated LEU Fuel

ENW retained ownership of 47 MTU of the DUEP material produced in 2012 and 2013, with plans to send this material to a nuclear fuel fabricator. DOE will work with TVA to preserve the (lack of) obligation status from this material on a separate LEU inventory. At DOE's request, TVA is pursuing the ability to store these obligation "flags" at enrichment or fabrication facilities using third-party inventories. Certain nuclear fuel suppliers have indicated they are willing to "book" and store flags for TVA by using their reserve LEU as the underlying commodity to hold these flags. ENW's 47 MTU would provide approximately one reload for a tritium production reactor. Negotiations to implement this approach are expected to be completed in FY 2015.

Costs for book storage are expected to be no more than \$2-4 million per year and are included in the Tritium Readiness Program budget requests.

Westinghouse Fuel Flags and TVA Reserve

Other potential sources of obligation “flags” are from domestic utilities that still have unobligated uranium in inventory that came from PGDP or from down-blended excess HEU. Westinghouse, through the barter portion of the DOE contracts for down-blending, currently has 1 reload (~40 MTU) of unobligated uranium. DOE has arranged for this material to be retained for future use in tritium production reactors through existing contracts between TVA and Westinghouse.

In addition to the Westinghouse material, TVA has in their reserves 1.5 reloads of unobligated LEU, currently stored at a fuel fabricator, which can be used for either obligation exchanges or directly in a TVA tritium producing reactor.

Table 2. Option 1: Preserve Additional Sources of Unobligated Uranium

Project	Available Material	Single Reactor Reloads	Extends Tritium Production Until	Relative Cost to DOE	Risk
Preserve obligation-free status of ENW portion of DUEP LEU	47 MTU at 4.4%	1	2028	Low	Low—Covered under the Interagency Agreement; however, a modification may be required
Preserve unobligated Westinghouse Fuel Flags	43 MTU at 4.4%	1	2029	Low	Low—Covered under the Interagency Agreement; however, a modification may be required
TVA reserves	60 MTU at 4.4%	1.5	2030	Low	Low—Covered under the Interagency Agreement, however, a modification may be required.

Option 2. Repurposed Excess Uranium

DOE is currently implementing a new excess HEU down-blending program, the Repurposed Excess Uranium (REU) Program. REU is intended to down-blend a total of 13.4 MTU of excess HEU. This program began in early 2015 and is expected to run for approximately 4.5 years. The program will produce approximately 279 MTU of 4.95 percent LEU. The REU program, like previous down-blending programs such as the AFS and MOX Back-Up Fuel program, is intended to be funded as a barter arrangement. NNSA plans to compensate the commercial down-blender with a portion of the derived LEU product. Due to increases in down-blending costs and reduced market value of LEU, most of the LEU produced is expected to be used as compensation.

Of the total 13.4, just over 11 MTU is derived from the unencumbered E05 declaration. The unencumbered HEU will produce 210 MTU of unencumbered and unobligated LEU. DOE is

working with TVA to make arrangements to ensure that the resulting unencumbered and unobligated 210 MTU of LEU will be preserved for use in the TVA reactors. This could fuel the TVA tritium production reactors for five single-reactor reloads.

Because of contracting difficulties, a contract for just the first 3 MTU of HEU planned for the REU Program —representing about a year’s worth of down-blending—has been signed. This contract for the initial 3 MTU was structured as an extension of the MOX Backup LEU Fuel Inventory agreement. The 3 MTU will produce 64 MTU of 4.95 percent LEU, of which about 50 MTU is from the unencumbered and unobligated E05 declaration.

Procurement actions for the remaining 10.4 MTU are underway. This 10.4 MTU is expected to produce 215 MTU of 4.95 percent LEU, of which 160 MTU will be unencumbered and unobligated. The primary impediment in contracting for down-blending the 10.4 MTU is the barter arrangement. While this has worked well for the previous down-blending campaigns, declining market values for EU over the last four years has reduced industry’s interest in being compensated for services with a portion of the derived LEU.

One option to reduce contracting difficulties would be to pay for the purification and down-blending of the remaining 10.4 MTU using appropriated funds rather than barter. This would cost NNSA approximately \$373 million but would result in the entire 215 MTU of LEU remaining with NNSA (only the 160 MTU mentioned above would be unencumbered and unobligated; the remaining 55 MTU would be encumbered but unobligated). An estimated \$373 million to produce 215 MTU of LEU results in a unit cost of \$1674/Kg of uranium of 4.95 percent LEU. This is \$53/Kg of uranium below the current market price for 4.95 percent LEU and is therefore less than what NNSA would expect to pay TVA to acquire LEU from the market in Option 1. Note that this cost should be largely offset by TVA’s avoided fuel costs since this material will be provided to TVA for fabrication into fuel, allowing TVA to avoid purchasing fuel on the commercial market. Table 3 shows the estimated costs and timing of expenditures for the remaining 10.4 MTU of the REU program. These costs include preparing the material to ship from Y-12, purification, and down-blending at commercial facilities.

Table 3. Cost Profile for Option 2 if Appropriated Funds are Used

	FY 2016	FY 2017	FY 2018	FY 2019
Annual Total	\$105	\$106	\$110	\$52
Cumulative Total	\$105	\$211	\$321	\$373

Escalated costs, in millions

Option 3. Down-Blending National Security and Excess HEU

The UIWG has developed an option that would provide unencumbered and unobligated HEU material from a combination of existing National Security and excess inventories. Down-blending this material could produce more than 400 MTU of 4.75 percent LEU, which would provide 10 individual reactor reloads or fuel for eight years of continuous tritium production with two reactors. There are significant advantages, costs, and some mid-level risks associated with this option.

Source materials for Option 3 were selected based on the intent to preserve the most valuable materials for National Security missions. Source materials include National Security and unencumbered Nuclear Nonproliferation materials from the 2005 Excess Material Declaration (E05) along with certain Excess Other (EOT) materials.

Most of the EU comes from National Security material in forms that require extensive processing in order to meet mission requirements and exceed current processing capability. The inventory also considered projected future program-generated National Security inventories (created as a by-product of metal production) that exceed recovery processing capabilities and capacity. Other materials include:

- National Security material of a lower assay more suitable for down-blending to preserve higher assay HEU with known requirements;
- projected intermediate enriched uranium unalloyed metal from dismantlement;
- material scrap (≥ 20 percent assay) from uranium-molybdenum production, Advanced Test Reactor (ATR), High Flux Isotope Reactor, etc.;
- remaining Y-12 E05 and EOT inventories of various forms;
- some Advanced Recovery and Integrated Extraction System oxides in storage at Los Alamos National Laboratory; and,
- National Security material that is in a usable form to meet customer demand but is less attractive because of identified impurities or morphology concerns.

This option uses a Nuclear Regulatory Commission (NRC)-licensed commercial processor for HEU purification and down-blending services to produce unobligated and unencumbered LEU for tritium production purposes.

There are several benefits associated with down-blending this material. Based on long-range processing and capability assessments, current and future recycle and recovery capabilities and capacity are insufficient to process the materials in this backlog for many decades, even considering Y-12's forecast transition to the new Uranium Processing Facility. The majority of these materials are not in a form suitable for long-term storage without processing and packaging. This material is considered a good candidate for down-blending because it contributes to reduction of the backlog, supports the transition effort to prepare for the Uranium Processing Facility, and reduces safety risk by converting materials to a form suitable for reuse in a timely manner. If this material is not used in the near-term for down-blending, NNSA will have to redirect limited resources and funds to prepare the materials for long-term storage until a disposition or utilization path is identified. This option will also reopen a recovery processing pathway for various scrap materials held by non-Defense Programs (DP) programs (e.g., reactor fuel scrap).

Based on historical throughput at Y-12, the delivery schedule for these materials was estimated at six years (FY 2019 through 2025). The project start date is not projected until FY 2019 since

most of the proposed HEU is oxide, and all of the oxide-type blending/packing capacity at Y-12 will be occupied from FY 2015 through FY 2019 with the REU down-blending project. Because a large portion of the planned source material will be generated over the FY 2015 to FY 2020 time period, there is risk associated with the accuracy of projected quantities due to potential changes in production and dismantlement operations. Therefore, the material options should be re-evaluated annually as inventories are realized and other programmatic scrap is generated within the DOE complex.

A rough order of magnitude financial estimate indicates that producing the LEU will require an estimated \$117 million in funding to pay for Y-12 processing costs and \$653 million in commercial down-blending costs (including diluent purchases and LEU processing, storage, and inventory management charges) for a total of \$770 million when escalated. This is 86 percent of what the LEU would cost to purchase on the commercial market if unobligated material were available—a savings of approximately \$90 million. This cost should be largely offset by TVA avoided fuel costs since this material will be provided to TVA for fabrication into fuel, allowing TVA to avoid purchasing fuel on the commercial market. Table 4 shows the projected costs (with escalation) and timing of expenditures for Option 3. The processing at both Y-12 and Nuclear Fuel Services is similar in scope to the REU program.

Table 4. Cost Profile for Option 3

	FY 2019	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025
Annual Total	\$6	\$121	\$125	\$131	\$135	\$139	\$113
Cumulative Total	\$6	\$127	\$252	\$383	\$518	\$657	\$770

Escalated Costs, in Millions

Option 4. HEU from Defense Programs Strategic Reserve

As required by Presidential mandate, DOE/NNSA must “... maintain a Strategic Reserve of special nuclear material and tritium.”¹⁶ The current composition of the HEU Strategic Reserve includes canned subassemblies (CSAs), composite pits, very highly enriched uranium (VHEU), and high purity metal. The HEU Strategic Reserve is required to ensure an HEU supply is available for the weapons program in the future. Additional HEU is held in components for potential reuse in Life Extension Programs (LEPs) or to support shelf-life and surveillance programs. While the composition of the Strategic Reserve may change to lower levels while supporting the New START stockpile, changing the quantity of HEU retained requires Presidential approval.

The material that is not contained within components (CSAs and composite pits) is primarily VHEU (HEU enriched to ~97 percent) and is a scarce, high-value resource. The VHEU is being held in case the 93 percent assay stream becomes degraded and would be used to re-enrich the

¹⁶ Presidential Policy Directive (PPD)-9, July 15, 2011

stream back to 93 percent. Therefore, use of VHEU for tritium production was not further considered.

The remaining material from the Strategic Reserve is still in CSAs and composite pits, which would require significant processing and disassembly to access the HEU unalloyed metal. These CSAs and pits are not currently in the disassembly baseline scope of work and would require analysis to determine the feasibility and cost for disassembly to access the material.

Option 3 was developed based on the intent to preserve unalloyed metal in the HEU inventory with an assay of 93.15 percent to meet DP, Naval Reactor (NR), and High Assay Research Reactor missions and to reduce the backlog of HEU in forms awaiting chemical recovery and/or conversion to a usable form. The quantity of HEU used in Option 4 could be adjusted to produce whatever quantity of LEU was needed. Costs for Option 4 would be similar to Option 3, with the addition of dismantlement and disassembly costs. As noted above, drawing down the Strategic Reserve below the PPD-9 requirement would require Presidential approval. Using the DP material identified in Option 3 and leaving the Strategic Reserve HEU for its intended purpose minimizes the projected shortfalls and allows DOE/NNSA to down-blend backlog material that has no near-term use in its current form.

Option 5. HEU from DOE-Owned Irradiated Nuclear Fuel

DOE currently has a sizeable inventory of spent nuclear or used fuel (SNF). This includes spent NR fuel at Idaho that is part of the National Security inventory; mixed SNF including additional NR material that is listed under the S94 declaration (and thereby carrying peaceful use encumbrances); and other material (including NR fuel), primarily located at Idaho, containing a mix of obligations and encumbrances. There is no SNF designated as EO5.

Some of this SNF inventory contains recoverable HEU. SNF stocks consist of both aluminum-clad and non-aluminum clad inventories. At present, the United States can only process and recover HEU from aluminum-clad SNF using the H-Canyon facility located at SRS. The capability to process non-aluminum-clad SNF (e.g., zirconium or stainless steel clad) to recover HEU was lost when the Idaho National Laboratory (INL) Chemical Processing Plant and the Hanford PUREX facilities ceased operations in the early 1990s and were decommissioned.

While most of the inventory of aluminum-clad SNF is stored at SRS, some of this material is at INL. Future returns of aluminum-clad SNF from foreign and domestic research reactors are all planned to be received at SRS. Nearly all of the SNF currently at SRS is either encumbered with policy restrictions from the S94 declaration or bound by foreign peaceful use obligations.

Aluminum-Clad Spent Nuclear Fuel

It would be possible to perform a “swap” of SNF between INL and SRS to support the disposition of aluminum-clad SNF. The aluminum-clad SNF currently located at Idaho would be shipped to SRS, and SRS would ship the non-aluminum-clad SNF currently in storage at SRS to Idaho. The aluminum-clad SNF would then be processed at SRS.

The available aluminum-clad SNF at Idaho is from the ATR. If the decision was made to recover the available EU and down-blend to an enrichment of 4.95 percent, approximately 62 MTU of LEU could be produced over an extended period of operation (at least a decade). This option was evaluated in FY 2009-2010. The total cost for the SNF movement between SRS and INL was approximately \$300 million (in addition to the \$200 million annual cost to operate the SRS H-Canyon, which is covered by the base Environmental Management program). The low estimated throughput and cost associated with operating H-Canyon, coupled with the \$300 million estimate for swapping the material, makes this option an unattractive short-term solution to support tritium production. In addition, about one-fourth of the SNF available is covered by the S94 surplus material declaration and therefore is subject to U.S. policy encumbrances.

Zirconium-Clad Spent Nuclear Fuel

In addition to the potential for processing the aluminum-clad ATR SNF at SRS, the Office of Nuclear Energy is researching a process called ZIRCEX that could assist in the recovery of HEU from zirconium-clad spent naval reactor fuel. Excluding the naval spent fuel with S94 restrictions, there is a substantial quantity of HEU in naval spent fuel inventories that would be unencumbered and unobligated. Naval SNF currently contains enough HEU to produce approximately seven reloads of unencumbered and unobligated LEU. As the Navy continues to defuel submarines and aircraft carriers over the coming years, additional naval SNF will become available; however, the delivery rate would not fully support tritium requirements.

The ZIRCEX process as envisioned currently would remove the zirconium cladding, leaving the fuel components to be dissolved for recovery of the HEU through an existing solvent extraction process. Proof-of-concept testing is currently underway with positive results at the laboratory scale. A pilot-scale demonstration and testing project is planned to prove its effectiveness but is still waiting on funding. ZIRCEX is promising for waste management reasons because it may avoid or reduce the use of hazardous reagents while generating a substantially lower volume of liquid high-level waste. It also provides an alternate disposition path for naval spent fuel to meet regulatory requirements and agreements with the State of Idaho.

A feasibility study is underway to determine what would be required to use HEU from processed naval SNF to make LEU for tritium production. Early analysis suggests that additional processing would be required after the ZIRCEX front-end de-cladding to separate HEU from high-activity fission products, purify the HEU solution to meet commercial fuel specifications, and finally down-blend to LEU. H-Canyon at SRS is the only operating facility that could do the reprocessing at this time unless a new or modified facility was developed at INL where ZIRCEX is being developed and the naval SNF is located. Implementation uncertainties for this option include potential budgetary or programmatic obstacles and the need to complete environmental reviews and qualify waste forms for disposal.

Although the solvent extraction step should remove most of the transuranic and fission products from the HEU, minor isotopes of uranium (i.e., ^{236}U) in the spent fuel cannot be

removed. The LEU derived from such spent HEU fuel is considered “off-specification” because the isotopic composition does not meet the applicable commercial fuel specifications.

Use of off-specification LEU in commercial nuclear power plants requires a special amendment to the NRC operating license. At present, only TVA uses off-specification fuel in a CLWR. TVA has been successfully using off-specification fuel from processed DOE SNF in its Browns Ferry plants since 2005 (Sequoyah is also authorized to use this material). However, both off-specification fuel use and tritium production places substantial quantities of neutron-absorbing materials in the reactor core. This requires an increase in the ²³⁵U content of the fuel and changes the operating characteristics of the core. There is a risk that TVA and/or NRC would be reluctant to combining these effects in a single reactor.

Another issue is that an exchange of encumbrances from the off-specification LEU to clean LEU may not be possible since the donor and receptor materials in such an exchange should be of equivalent quality, and off-specification LEU derived from processed HEU may not qualify as equivalent to on-specification LEU produced from un-irradiated uranium.

Because the ZIRCEX technology is still in the early stages of development, it would be premature to estimate schedule or costs for design, construction, and licensing of a new naval reactor spent fuel processing capability based on ZIRCEX. Likewise, given the anticipated scope of post-ZIRCEX processing requirements and issues, the UIWG considers the use of ZIRCEX for recovery of unobligated HEU for tritium production only a long-term possibility that should be re-evaluated as the technology matures.

Table 5 summarizes Options 2, 3, and 4, and their potential impact on tritium production. Figure 5 shows the combined effect of all of the discussed options on providing fuel for two TVA tritium production reactors.

Table 5. HEU Down-Blending Options for Unobligated LEU Fuel

Project	Available Material	Single Reactor Reloads	Extends Tritium Production Until	Relative Cost to DOE	Risk
Option 2: Repurposed Excess Uranium	13.4 MTU HEU	5	2033	Low	Moderate—Needs contract and concerns with funding arrangement
Option 3: Down-Blend National Security and Excess HEU		10	2041	Moderate	Moderate—Requires appropriations that may be offset by savings in fuel costs
Option 4: Down-Blend Strategic Reserve HEU		As Desired	Determined by quantity selected	Moderate/High	Requires change to PPD-9, change in Dismantlement plans
Option 5: Purify and Down-Blend Spent Fuel		Up to 20	Unknown	Very High	Very High—Expensive Capital project with low throughput for Al-clad fuel and long-term development risks for Zr-clad recovery processes

Fiscal Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Fuel Source	Existing Fuel Sources												Possible Fuel Options			
	USEC			Energy Northwest (ENW)						MOX Backup LEU			TVA Reserves			
Reactor 1	Reload # 14	Reload # 15	Reload # 16	Reload # 17	Reload # 18	Reload # 19	Reload # 20	Reload # 21	Reload # 22	Reload # 23						
	1	1	3	5	7	9	1	3	1	3						
Reactor 2		Reload # 3	Reload # 4	Reload # 5	Reload # 6	Reload # 7	Reload # 8	Reload # 9	Reload # 10	Reload # 11						
		2 (Cleanout)	4 (Cleanout)	6	8	10	2	4	2	4						

Fiscal Year	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Fuel Source	Possible Fuel Options												Future			
	REU				DBOT						To Be Determined					
Reactor 1	Reload # 24	Reload # 25	Reload # 26	Reload # 27	Reload # 28	Reload # 29	Reload # 30	Reload # 31	Reload # 32	Reload # 33						
	1	3	5	2	4	6	8	10	2	4						
Reactor 2	Reload # 12	Reload # 13	Reload # 14	Reload # 15	Reload # 16	Reload # 17	Reload # 18	Reload # 19	Reload # 20	Reload # 21						
	2	4	1	3	5	7	9	1	3	5						

KEY:

Existing Fuel Sources	USEC: The last deliveries of approximately 20 MTU from TVA's contract with USEC
	Energy Northwest: ENW will deliver ~ 435 MTU of LEU from the Depleted Uranium Enrichment Project
	MOX Backup LEU: LEU inventory from the MOX fuel program to be used for obligation exchanges
Possible Fuel Options	TVA Reserves: Strategic fuel reserves and other unobligated fuel available via TVA
	REU: LEU derived from the Repurposed Excess Uranium down-blending program
	DBOT: LEU derived from down-blending a mix of excess and NS HEU
Future	To Be Determined

Figure 5. Combined Effect of LEU Fuel Options for TVA Tritium Production Reactors

Alternate Tritium Supply and Production Technologies

Although tritium was produced previously in the United States using heavy water nuclear reactors and is currently produced with CLWRs, other methods of production are possible. Some alternatives include particle accelerators and advanced reactor technologies, such as small modular reactors (SMRs) and gas-cooled reactors. According to a Congressional Budget Office assessment in 1998, development of any of these alternatives to support the quantity of tritium production necessary to meet the needs of the NWS would require considerable capital investment for research, development, deployment, and operations. The Congressional Budget Office confirmed that the CLWR option for producing tritium was the most cost-effective approach.¹⁷ Although DOE continues to monitor commercial developments in reactor technology to identify opportunities to reduce dependence on limited sources of unobligated uranium fuel, this conclusion is still valid today.

Additional information on these alternative advanced reactor technologies is provided in a 2014 DOE/NNSA Tritium Production Future Technology Study¹⁸ and the CLWR SEIS. A summary discussion of these technologies is presented below.

Particle Accelerators

Particle accelerator production of tritium was extensively studied¹⁹ by DOE leading up to the CLWR Record of Decision in 1999²⁰ and has been shown to be technically feasible. The viability

¹⁷ Congressional Budget Office report, "Estimated Budgetary Effects of Alternatives for Producing Tritium," August 27, 1998, <http://www.cbo.gov/publication/11108>.

¹⁸ U.S. Department of Energy, "Tritium Production Future Technology Study", Revision 0, April 2014.

¹⁹ JASON Panel Report, JSR-92-310, "Accelerator Production of Tritium (APT)," January 1992.

of particle accelerator tritium production as an alternative was reviewed based on factors such as target fabrication and tritium extraction technology and infrastructure, capital and operating costs for a new particle accelerator facility, and environmental impacts. The 1999 decision to produce tritium using a CLWR approach versus that of the Accelerator Production of Tritium Program (APT), was heavily influenced by the APT's need to construct a new facility, requiring a capital investment of several billion dollars.²¹

Advanced Reactor Technologies

The Tritium Production Future Technology Study²² evaluated possible alternatives to CLWR tritium production in the event another option is needed for risk mitigation and to consider next generation technologies that may be viable to fulfill the tritium production mission in the future. For this study, a team of subject matter experts surveyed a wide range of technological alternatives to the CLWR approach for providing the neutrons needed for tritium production. These alternatives were evaluated against a number of criteria, considering technological feasibility, lead time, risks, costs, fuel usage, etc.

The evaluations considered integral pressurized water reactors, also known as SMRs; sodium-cooled, fast flux reactors; molten salt reactors; fluoride salt-cooled, high temperature reactors; heavy water reactors; modular high-temperature, gas-cooled reactors; and a natural uranium-fueled, heavy water reactor. Table 6 contains information about the reactor technologies that were reviewed and their associated Technology Readiness Levels (TRLs).²³ Higher TRLs indicate commensurately higher levels of technology maturation. A TRL of 1 is associated with published research while a TRL of 9 indicates an operating, proven process.

This study found that if TVA is not able to continue tritium production, the two most viable alternatives are to either enlist the support of another domestic nuclear reactor operator or to invest in four SMRs for tritium production. From a cost standpoint, the alternative of enlisting a domestic operator is superior to the SMR option. Installing SMRs to make tritium would likely involve capital costs commensurate with purchasing an existing, full-scale CLWR. The main benefit of the SMR is that it can be installed in increments, therefore making the risks, lead-times, and financing more tenable to a utility owner. Modular off-site construction should reduce fabrication costs, which may be offset by increased costs due to less operating efficiency caused by scale and reduced electric power sales to carry a portion of fixed costs. Sodium-cooled fast reactors have a longer development lead time and higher costs, but fewer units would be required.

²⁰ Consolidated Record of Decision for Tritium Supply and Recycling. U.S. Department of Energy, Federal Register Vol. 64, Number 93, May 14, 1999, pp. 26369 – 26386.

²¹ Congressional Budget Office report, "Estimated Budgetary Effects of Alternatives for Producing Tritium," August 27, 1998, <http://www.cbo.gov/publication/11108>.

²² U.S. Department of Energy, "Tritium Production Future Technology Study," Washington, DC, April 2, 2014.

²³ DOE G 413.3-4A, Technology Readiness Assessment Guide, September 15, 2011.

Table 6. Evaluation of Advanced Reactor Technologies

Alternative Technology	Design	Fuel	Tritium Production g-T/kg- ²³⁵ U	TRL
Base Technology - CLWR	Westinghouse	<5% ²³⁵ U UOX	0.48-0.56-1.306	8
Integral Pressurized Water Reactors	mPower, Westinghouse, Holtec, NuScale	<5% ²³⁵ U UOX	0.40-1.40	4-5
Sodium Fast Reactor	PRISM, EBRIII, FFTF, TerraPower, ARC-100	10-20% ²³⁵ U Metal or oxide (²³⁸ U & MOX)	~6.87	4-6
Advanced Test Reactor	ATR-General Atomics	93% ²³⁵ U Uranium Aluminide (UAlx)	3.77	7
Molten Salt Reactor	Transatomics, Flibe	1.8-33% ²³⁵ U Salt (LiF-BeF ₂ -ZrF ₄ -UF ₄), LiF-(Heavy metal)F ₄	TBD	3-5
Fluoride Hi-Temp	FHR	10-20% ²³⁵ U TRISO	TBD	2
New Production Reactor	Heavy Water, High Temp Gas Reactors	93% ²³⁵ U Metal or TRISO	4.34	5-6
Natural Uranium-Fueled, Heavy Water Reactor	Enhanced CANDU 6	.71% ²³⁵ U UOX	TBD	7

Current industry plans for licensing and installation of the first generation of SMRs are still uncertain, and the best case schedule estimates show initial operational capabilities beginning in 2022. With the modifications required to host TPBARs, SMR production of tritium might be feasible in the mid-2020s.

Eventual deployment of SMRs by U.S. utilities will depend on many factors, including energy market fluctuations, NRC licensing requirements, coal/fossil energy regulation, Environmental Protection Agency restrictions, natural gas supply and demand, financing capital costs, etc.; however, DOE's research and utility and industry investment in SMR development activities continues in earnest. These factors will continue to impact the timing of SMR construction and operation, so the availability of SMRs for tritium production is uncertain.

As for an alternative CLWR, a best-case schedule estimate is that tritium production could begin in the early 2020s given the lead-times required for solicitations, planning, engineering analysis, licensing, and loading reactor cores with unobligated fuel. The current tritium inventory level could not be supported by either of these options without using available reserves and requiring some reductions in the number of deployed reservoirs. In terms of costs, risks, and lead-times, there are backup plans and contingency options, but no good alternatives to irradiating TPBARs in TVA reactors.

IV. Demand for HEU and High Assay LEU

NNSA is responsible for a number of national security missions that require a reliable supply of EU in varying assays and forms. The EU requirements are shown in Table 7 in terms of mass, enrichment, and peaceful use restrictions as follows:

- HEU to maintain the nuclear weapons stockpile;
- HEU to fuel naval reactors;
- HEU in support of Mutual Defense Agreement(s);
- HEU to fuel research reactors for medical isotope production and other research applications (e.g., prior to conversion to LEU fuel);
- HEU for future NASA reactors and other research purposes; and,
- High-assay LEU (<20 percent ²³⁵U) to fuel research reactors for medical isotope production and other research applications.

Table 7. Summary of Enriched Uranium Demand Through 2060

Demand	Enrichment (% ²³⁵ U)	Mass (MTU)	Requires Unobligated EU	Notes
HEU Demand				
Nuclear Weapons Stockpile	>20%	<i>Classified</i>	Y	<i>See Classified Appendix C</i>
Naval Reactors	>92%	128.3	Y	Does not include allocations for a new class of nuclear ship
Mutual Defense	>92%	<i>Classified</i>	Y	<i>See Classified Appendix C</i>
HEU Isotope & Research Reactors	>92%	4.0	N	Assumes conversion to high-assay LEU by 2030
Space Reactors	>92%	2.3	N	Material for space power and propulsion needs for NASA and other users through 2060
Defense Reactors	>92%	0.9	Y	Pulse-type reactor for testing

High-Assay LEU Demand				
High-assay LEU Research Reactors	>5% to <20%	232.4	N	Supports nonproliferation programs

Nuclear Weapons Stockpile

The U.S. NWS contains the largest quantities of existing HEU reserves; however, it does not consume any additional HEU, except for minor quantities disposed of as production losses as a consequence of weapons refurbishment. The NWS demand consists of active stockpile units, inactive intact units, component and material reserves, and working inventories.

As components from retired nuclear weapons are dismantled, the HEU they contain becomes available for re-use within the NWS or to satisfy other missions and commitments. The existing inventory of HEU contained in nuclear weapon components is a finite and diminishing source of HEU.

When HEU for the weapons program is identified as surplus or excess to NWS needs, it is used for other programs after undergoing a review and allocation process.²⁴ The recycle and reuse of NWS material requires significant processing and purification to remove impurities from scrap generated during manufacturing operations.

Naval Nuclear Propulsion Reactor Fuel

HEU recovered from retired weapons and NR process scrap will support known NR demand through 2060. Projected deliveries of excess HEU for NR use are presented in Table 8. It should be noted, however, that any new applications of naval nuclear propulsion beyond the current fleet plan would accelerate the consumption of existing HEU.

Table 8. Naval Reactors HEU Deliveries Through 2060

Time Period	Annual Requirement (MTU)	Total Requirement (MTU)
FY 2012–FY 2020	3.6	32.3
FY 2021–FY 2030	2.8	28.0
FY 2031–FY 2040	2.5	25.0
FY 2041–FY 2060	2.15	43.0
Total		128.3

²⁴ Surplus is a subset of the excess inventory. The excess category means that the HEU is excess to the nuclear weapons stockpile needs but still may have national security requirements, like for Naval Reactors. Once excess HEU is declared surplus, the material can be made available for other uses beyond national security needs.

As shown in Figure 2, up to 160 MTU of the 200 MTU of HEU declared excess to the NWS in 2005 was allocated for naval nuclear propulsion. NR estimates this allocation will be sufficient to meet its demand through 2060, assuming no changes in projected fleet requirements.

In a 2014 report to Congress, NR evaluated the potential use of high assay LEU in lieu of HEU for naval propulsion and concluded that such a change would be uneconomical, impractical, and would negatively affect fleet operations, barring significant technological changes and advanced fuel development.²⁵

Spent HEU fuel from naval nuclear propulsion plants could be reprocessed, down-blended, and used for other purposes as discussed under Option 5. However, these reprocessing facilities were shut down in the late 1980s and have since been decommissioned and dismantled. Also, there are considerable technical challenges associated with these operations, and the EU product recovered contains unacceptably high concentrations of undesirable isotopes such as ²³²U and ²³⁶U.

The presence of these isotopes increases the complexity and cost of fuel fabrication and reactor operations. In addition, there are budgetary, programmatic, and environmental obstacles that must be overcome to develop this option.

Mutual Defense Agreement

The United States and the United Kingdom (U.K.) signed an agreement in 1958 for cooperation on the uses of atomic energy for defense purposes. This agreement is referred to as the U.S./U.K. Mutual Defense Agreement (MDA). The U.S./U.K. MDA enables the United States and the United Kingdom to exchange information and materials with the objective of improving each party's atomic weapon design, development, and fabrication capability. This includes development of defense plans; training of personnel in the employment of and defense against atomic weapons; evaluation of potential enemy capabilities; development of nuclear delivery systems; and, research, development, and design of military reactors.

The agreement also provides for the transfer of source, by-product, and special nuclear material, components, and equipment between the two countries and the transfer of non-nuclear components of atomic weapons to the United Kingdom.

The quantity, schedule, and details of possible nuclear material transfers in support of the U.S./U.K. MDA are classified.

Any potential supply of HEU for commitments of the U.S./U.K. MDA will be met from National Security inventories that have been reserved for this purpose. The same processes used to supply NR demand will be used to supply any MDA demand, if applicable.

²⁵ U.S. Department of Energy Office of Naval Reactors, *Report on Low Enriched Uranium for Naval Reactor Cores*, January 2014.

HEU for Isotope Production and Research Reactor Fuel

Since the start of the nuclear age, the United States has provided EU for research reactors, space reactors, and isotope production reactors that are not related to defense needs. The EU associated with these activities comes from a large but finite supply created before 1964. The United States provided more than 30 MTU of EU for research reactor use around the world, through 1996.

Although many research reactors in the United States and foreign nations have been converted to high-assay LEU under the DOE/NNSA Defense Nuclear Nonproliferation’s Reactor Conversion Program (an element of nuclear nonproliferation policy), conversion is not a standardized process applicable universally to all research reactors. Each system must be evaluated and fuel fabricated to match unique design considerations present at each facility. Accordingly, some research and isotope production reactors with complicated designs are more difficult to convert.

These reactors will continue to require HEU fuel until high-assay LEU fuel can be designed, tested, and delivered or until these reactors are no longer needed and shut down.

Space Reactor Fuel

HEU is required to support NASA’s and other U.S. Government users’ applications in space. While the timing of the demand is considered variable, Table 9 represents the best estimates of space reactor demand through 2060, as provided by DOE’s Office of Nuclear Energy.

Table 9. HEU Space Reactor Fuel Demand Through 2060

Reactor	Average Biennial Requirement (kgU)	Total Requirement (kgU)
FY 2010-2020 NASA Space Nuclear System Ground Test	20	100
FY 2020-2030 NASA Fission Surface Power System	100	500
FY 2030-2040	140	700
FY 2040-2060	100	1000
Total		2,300

Many of the same existing capabilities used to supply material for NR and research reactors would be used to supply space reactors. The fuel designs for space reactors could use uranium metal (alloyed metal), oxide, nitrate, or carbide form, for which HEU production processes will continue to exist.

Defense Reactor Fuel

Only one defense reactor, operated by the DOD, is currently operating. The DOD reactor is used to study defense-related nuclear weapon effects and is scheduled for a fuel replacement in 2018. This reactor will require fuel replacement on a 5-year schedule through the projection

period of this report in 2060. This replacement schedule will require 875 kg of uranium over this time period.

High-Assay LEU Research Reactor Fuel

A key component of Defense Nuclear Nonproliferation's (DNN's) efforts to minimize the civilian use of HEU is the DNN Office of Material Management and Minimization's Reactor Conversion Program, which began in 1978 as the Reduced Enrichment for Research and Test Reactor program. Through this program, DOE has partnered with research reactor owners around the world to convert reactors from the use of HEU fuel to high-assay LEU (>5 percent to <20 percent ²³⁵U) fuel. Successful conversion of these facilities essentially eliminates the risk of diversion and potential misuse of HEU, while allowing for continued operation to produce vital medical isotopes and conduct various research activities.

The Nuclear Nonproliferation Act of 1978 (Pub. L. 95-242) directed that the United States would be a reliable supplier of nuclear materials to countries that follow nuclear nonproliferation policy and nuclear programs not contrary to, and consistent with, U.S. national security interests. In support of these commitments and consistent with the Atomic Energy Act of 1954, as amended, as well as the USEC Privatization Act of 1996, as amended, DOE has an ongoing program to supply high-assay LEU and has entered into supply contracts and agreements for domestic and foreign research, isotope production, and test reactors.

The United States and other commercial enrichers have no capability to enrich uranium to assays above five percent ²³⁵U. At present, uranium needed for fuel above this enrichment comes from down-blending HEU to the desired ²³⁵U assay. The number of reactors that will depend on a reliable supply of high-assay LEU is expected to increase as the conversion activities continue and as new LEU-fueled research reactors are built.

Current allocations of HEU for research and isotope production reactors, conversion schedules, and current plans for a domestic medical isotope production capability using high-assay LEU show that the supply designated for this purpose is projected to be exhausted by around 2030. After this date, additional supplies of high-assay LEU for research and isotope production reactors will have to be available, as well as for advanced reactor designs that may use high-assay fuels. In addition, HEU for reactors that are still in the process of conversion may be needed.

Research reactor fuel production generally begins with a high-assay LEU in metallic form. The current supply process to manufacture this material is to blend HEU metal with depleted or natural uranium metal to achieve the desired assay. Over the next decade, as additional research reactors convert to high-assay LEU, about half of the high-assay LEU demand will change to uranium metal alloyed with 10 percent molybdenum (assuming the fuel proves successful), with the remainder composed of all uranium metal.

Because of the technical challenges associated with producing this new uranium-molybdenum fuel, production scrap rates for this material are very high. While HEU scrap produced in

support of NWS or NR requirements is largely recovered and reused, there is no process available to recover scrap from high-assay LEU fuel production. New capabilities will have to be established to recover high-assay LEU. At present, high-assay LEU scrap is being stored pending a determination on the economic viability of deploying a capable recovery process. If recovery is determined to be economical and funding for deployment of a suitable technology is made available, the supply of high-assay LEU for research reactor use could be extended eight-to-10 years.

Existing Supply of High-Assay LEU

DOE does not maintain a stockpile of high-assay LEU (uranium enriched at least five percent but no more than 20 percent ²³⁵U). The Department does maintain a small working inventory of about 1 MTU of nominal 19.75 percent enriched material that it uses to supply fuel for approved research, space, and isotope production reactors. The working inventory is maintained by down-blending HEU that has been declared excess to U.S. national security needs. When the supply of available excess HEU is exhausted, an alternate source will be required.

V. Uranium Enrichment Technologies

Unencumbered Enrichment Facility

DOE/NNSA has identified the eventual need for an enrichment facility without peaceful use restrictions (i.e., a U.S.-origin facility) to produce HEU for NR fuel and high-assay LEU for research reactor fuel.²⁶ With the closure of PGDP, the need for a long-term supply of unobligated LEU power reactor fuel (e.g., 4.00 percent – 4.95 percent ²³⁵U) to support tritium production has added to this need. Depending on several supply and demand factors, and under current policy, this enrichment facility could be required sometime between the mid-2020s and 2060.

The design, size, and operation of an unencumbered enrichment facility that could accommodate naval fuel HEU requirements, research reactor high-assay LEU fuel needs, and LEU fuel for tritium production could consider leveraging commercial demand for enrichment services for LEU power reactor fuel from such a facility. Such a strategy could minimize the additional investment required by the U.S. Government to satisfy all of its needs for EU.

In response to Section 312(b) of Title III, Division D, of the Consolidated and Further Continuing Appropriations Act, 2015, quoted in Appendix B, DOE/NNSA established a team of federal, national laboratory, and contractor experts to perform an evaluation in December 2014 to identify and compare options for providing uranium enrichment capability to provide feed for reactor fuel in support of the tritium production program and research reactors, with the potential to produce highly enriched uranium for Naval Reactors.²⁷

The 2014 evaluation assessed each of the options against a standard set of criteria, thus providing sufficient detail and basis to support decision-making on a path forward; however, this evaluation did not make a recommendation for any specific option. The following enrichment options were evaluated:

- AC100 Centrifuges
- Small Centrifuges
- Electromagnetic Isotope Separation (EMIS)
- Paducah Gaseous Diffusion Plant (PGDP)
- Atomic Vapor Laser Isotope Separation (AVLIS)
- Separation of Isotopes by Laser Excitation (SILEX)

²⁶ Although LEU for research reactor fuel does not have to be free of peaceful use restrictions, it was included in this study because no commercial enrichment facility is licensed to produce high-assay LEU.

²⁷ U.S. Department of Energy, *Evaluation of Uranium Enrichment Technology Options*, DRAFT, April 2015

The following criteria were utilized by DOE in its evaluation:

- **TRL**—According to DOE Guide 413.3-4A, *Technology Readiness Assessment Guide*, ranking was done on a scale of 1 to 9, with 1 for technology in early research through 9 for a fully developed and deployed technology.
- **Cost**—Cost evaluation included “capital” cost to get the facility operational, including research and development, production facility and balance of plant design, procurement and component testing, construction, licensing, and startup. An estimate was also made for the annual steady-state operating costs of the facility. The cost of decommissioning and decontamination of the facility were not included.
- **Schedule**—An estimate was made of the high-level timeline showing the estimated durations for development, construction, startup, and operations to achieve a fully deployed facility capable of providing enrichments up to 4.95 percent.
- **Potential for Commercialization**—The evaluation considered the likelihood of each technology to be a viable commercial option for ^{235}U enrichment up to 4.95 percent. Leveraging commercial demand for these services could minimize the additional investment required by the U.S. Government to meet its needs for this material.
- **Mission Flexibility**—The evaluation considered how the technology selected might be adapted to produce high-assay LEU for research reactors and/or HEU for Naval Reactors.
- **Technology Source**—The evaluation considered whether or not there would be restrictions on the use and production of the EU based on foreign agreements or U.S. policy.
- **Risk**—The evaluation performed a qualitative analysis of the technical and programmatic risks associated with the unique characteristics and situation of each enrichment technology option.

The following paragraphs summarize each technology evaluated as of December 2014.

AC100 Centrifuges

The gas centrifuge is proven enrichment technology that is used in commercial enrichment facilities worldwide. The AC100 gas centrifuge from Centrus is a large (approximately 40 feet tall) centrifuge based on the design from DOE’s Gas Centrifuge Enrichment Plant program in the 1980s. The AC100 has been significantly updated to incorporate advancements in technology and manufacturing to increase the separation capacity and reliability of the machine.

The AC100 centrifuge is the most technically advanced and lowest risk option for future production of unobligated EU.

- The TRL is seven to eight and could be at a level of nine within 1-2 years.
- The capital cost is estimated to be \$3.1 billion to \$4.8 billion if build-out were started immediately and if adequate annual funding is assured. The annual operating cost

would be \$112 million to \$195 million per year. There is potential for commercialization in the long term.

- The technology is unobligated.
- The technology can be used to produce higher enrichment levels with the development of additional engineering and configuration processes.
- The risk level is low based on the extensive and recent research and development efforts for this technology.

Small Centrifuges

The small centrifuge option would be a new centrifuge based on DOE's current efforts to deploy a centrifuge for the separation of stable isotopes. The centrifuge machine that is currently being developed for isotope separation is too small to be usable for uranium enrichment, but it is possible that this machine design could serve as the conceptual basis for a new small uranium enrichment centrifuge.

Small centrifuges are a viable option for long-term EU production.

- The United States has developed this technology to a TRL of 3-4, and it could take approximately four to more than seven years to bring small centrifuges to a TRL of 9.
- The capital cost is estimated to be \$3.2 billion to \$6.8 billion, and the annual operating cost would be \$100 million to \$200 million per year.
- There is potential for commercialization in the long term.
- The technology would be unobligated.
- The technology can be used to produce higher enrichment levels with the development of additional engineering and configuration processes.
- Based on existing industry experience, there is low risk in the eventual development and deployment of this technology.

Electromagnetic Isotope Separation (EMIS)

EMIS technology was the first uranium enrichment technology developed by the United States during the Manhattan Project. A new EMIS isotope separator, based on the original technology, has been developed by Oak Ridge National Laboratory with the goal of separating stable isotopes.

EMIS is a proven technology for the separation of laboratory scale quantities of isotopes. When scaled for the production of SWU required for domestic uranium enrichment, the costs are unreasonable.

- The TRL is approximately seven and could reach nine within one-to-two years.
- At a cost of \$2.5 million per machine, the 60,000 machines would cost approximately \$150 billion. This cost does not account for the supporting infrastructure.

- Due to the cost, this technology would not be commercially competitive.
- This technology is unobligated.
- The technology can produce HEU but producing lower enriched assays would require that the EMIS product be down-blended.
- Due to the cost, this is a very high risk option.

Paducah Gaseous Diffusion Plant (PGDP)

The PGDP facility in Paducah, Kentucky, produced LEU from the mid-1950s until 2013. When the plant was shut down in 2013, it was taken off-line by removing the UF₆ inventory and backfilling with buffer gas. The plant was returned to DOE in October 2014, and DOE's Environmental Management program initiated decontamination and demolition activities. The option to restart the PDGP is attractive mainly because of its high production rate of 3.25M SWU per year (compared to the need for approximately 400,000 SWU/year required to meet a two-reactor tritium scenario).

Because of the precautions taken during shut down, and with major capital investments, it might still be possible to reconstitute and operate the plant for an estimated one-to-three years to produce a large stockpile of LEU. However, there are very high risks that the facility cannot be reasonably restarted due to degradation of equipment since shutdown, expected rate of equipment failure, a lack of replacement parts, and the dispersion of personnel. With any additional delay to a restart decision, the probabilities of a successful restart in less than 24 to 36 months is likely to be much less than 50 percent.

- The TRL was a nine at the time of plant shutdown but has regressed due to recent changes at the plant.
- This technology is no longer commercially competitive with gas centrifuge enrichment technology.
- This technology is unobligated.
- The existing plant is not capable of producing enriched uranium beyond nominally 5 percent ²³⁵U.
- The restart of PGDP is a high risk endeavor with significant chance of failure.

Atomic Vapor Laser Isotope Separation (AVLIS)

Several laser-based enrichment methods have been developed and demonstrated on a lab-scale or prototype basis. These methods hold the promise of being able to enrich uranium with relatively low power costs and much more efficiently than the gas centrifuge. The AVLIS method is based upon selectively ionizing ²³⁵U atoms. DOE began a research and development program at Lawrence Livermore National Laboratory in 1973 to develop AVLIS for possible use as a commercial enrichment technology. This effort was continued into the 1990s with private funding from USEC. However, after years of research, the further development of this technology was suspended, and there is no current effort underway.

- The AVLIS technology was developed to a TRL of 5-6 and could take anywhere from five-to-15 additional years of development to reach a TRL of nine. No current effort is underway to develop the AVLIS technology.
- There is insufficient information to estimate the capital or operating costs.
- There is a possibility this technology could be commercialized if a significant development effort is undertaken.
- This technology is unobligated.
- Additional scientific and process development work would be required to produce higher assay enrichments.
- There are high technology and high schedule/cost risks.

Separation of Isotopes by Laser Excitation (SILEX)

Another potentially promising laser-based enrichment method is the Separation of Isotopes by Laser Excitation (SILEX). Global Laser Enrichment is developing this technology but has recently indefinitely postponed plans to build a commercial SILEX facility in the U.S. This is a proprietary technology developed, in part, by an Australian company. Therefore, its use to produce unobligated material is currently considered prohibited based on the agreement between the United States and Australia Concerning Peaceful Uses of Nuclear Energy entered into pursuant to section 123 of the Atomic Energy Act of 1954.

- Due to the proprietary nature of this technology, the TRL is difficult to determine, but it is estimated to be 3. Global Laser Enrichment had suspended its planned development and demonstration program.
- There is insufficient information to estimate the capital or operating costs.
- If a significant development effort is undertaken, then possibly this technology could be commercialized.
- Its use to produce unobligated material is currently considered prohibited based on a Section 123 Agreement.
- Additional scientific and process development work would be required to produce higher assay enrichments.
- There is high technology risk and high schedule/cost risk based on experience with AVLIS development, which took approximately 15 years to move from a TRL of two-three to six.

Observations

Provided below are some of the key observations resulting from the analysis of the options:

- The EMIS technology is not a viable option under any circumstances due to the exorbitantly high capital and operating costs.

- Restart of the PGDP is increasingly risky with a significant chance of failure to produce any meaningful quantity of EU. A major effort would be required to reconstitute a functioning plant, and the timeline and cost to do so is a high risk endeavor due to the ongoing degradation and condition of the facilities and the significant dispersion of trained and qualified personnel since the plant was shut down in May 2013 and turned over to EM for decontamination and demolition in October 2014.
- The small centrifuge and AC100 options could be implemented with low technology risk if EU is needed after 2020 and before 2030.
- If EU is not needed until after 2030, then AVLIS is a potential option. This option would require a substantial demonstration effort for the potential rewards of a high efficiency process.
- SILEX is not a viable option under existing international agreements. In any case, this option would require a substantial demonstration effort for the potential rewards of a high efficiency process.

Other Sources of LEU and NU

Another potential supply source for EU would be to purchase high-assay LEU, LEU, or natural uranium on the commercial market; however, this strategy has significant limitations that may prove to be unworkable. It may be possible to purchase high-assay LEU from Russia (through the commercial enterprise TENEX) for the research reactor program demand. However, Russia currently supplies small quantities of high-assay LEU research reactor fuel in a different chemical form than used by DOE-supplied research reactors. Discussions should also be opened with commercial entities to explore their interest in supplying high-assay LEU up to 19.75 percent ²³⁵U. However, given the costs of licensing and facility modifications, along with the relatively small business volume (60,000 SWU/year), commercially derived high-assay LEU fuel may ultimately prove to be too costly for many research reactor institutions.

Whether the high-assay LEU could become available from foreign government or commercial sources, the material form would have to be converted to uranium metal for use as research reactor fuel, making development of a conversion facility capable of converting high-assay enriched UF₆ to metallic form a critical need.

Cost Estimate for a New AC100 Facility

DOE conducted a detailed cost estimate to build out domestic uranium enrichment national security plant based on the AC100 technology in part because this technology was found to have a low risk among the enrichment technology options and because there is actual cost data for the existing centrifuges.²⁸ The estimate assumed that an AC100 centrifuge enrichment facility would be located in Piketon, Ohio, at the site of the demonstration cascade that was funded in part through a cost-sharing Research, Development, and Demonstration Cooperative

²⁸ U.S. Department of Energy, *Cost Estimate Review of Centrus Energy Piketon Facility Buildout Scenarios*, DRAFT, January 2015. Costs are currently being verified by an independent entity.

Agreement with DOE and Centrus. It was assumed that the facility would produce approximately 400,000 SWU per year, requiring approximately 1440 centrifuges configured into two trains. This capability would support the tritium production requirements shown in Table 10.

Table 10. Tritium Production Cumulative SWU Requirements

		Tritium Production - Cumulative SWU Requirements (MSWU)													
			FY29	FY30	FY31	FY32	FY33	FY34	FY35	FY36	FY37	FY38	FY39	FY40	FY41
TPBARs	SWU/reload	Cum. Reloads	1	3	4	5	7	8	9	11	12	13	15	16	17
1104	286,227	MSWU	0.3	0.9	1.1	1.4	2.0	2.3	2.6	3.1	3.4	3.7	4.3	4.6	4.9
1504	315,510	MSWU	0.3	0.9	1.3	1.6	2.2	2.5	2.8	3.5	3.8	4.1	4.7	5.0	5.4

Detailed cost, risk, and schedule estimates were developed for a base case using data and input from DOE/NNSA, external consultants, and Centrus. Actual cost data was used, where possible, from the Research, Development, and Demonstration project or from Centrus' own experience. A work breakdown structure and assumptions were developed for several scenarios with variations in schedule and funding profile and estimates were adjusted to include fee and DOE oversight. Each scenario was assessed for project estimate definition and project life-cycle maturity using DOE Guide 413.3-21, *Cost Estimating Guide*.

DOE analyzed a wide range of implementing scenarios to ensure consideration of all available options. Two scenarios represent the range of practical build out options and are presented in this section. The first addresses near-term build-out to minimize costs. Remobilization of the manufacturing and engineering/procurement industrial bases would begin immediately to reduce loss of personnel expertise and supply chain disruption and is estimated to take approximately 27 months before construction could begin. Assuming full funding for this option, the first train could begin production in 2022 and be producing one reactor reload worth of EU every 15 months. The national security plant could be fully operational by 2025. Total cost for this option is estimated to be between \$3.1 billion and \$11.3 billion.

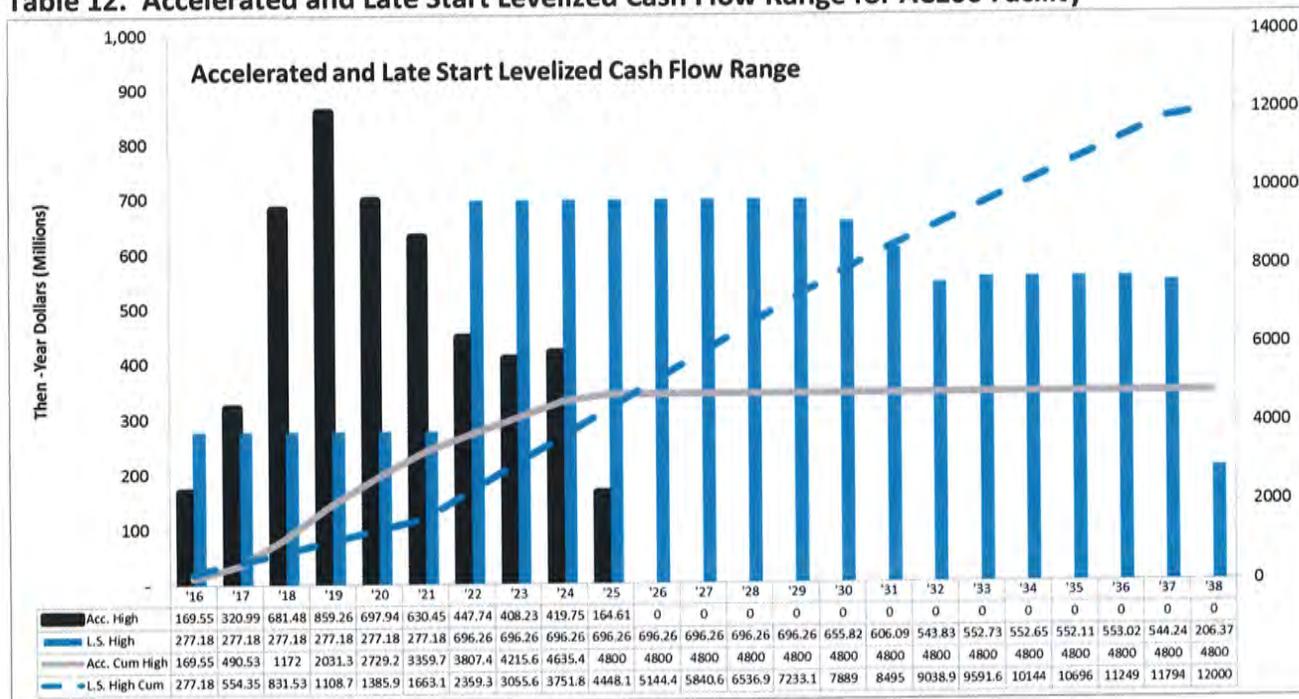
A second option takes into account the availability of uranium from the inventory and addresses late-start build-out. If funding were provided to use the first three uranium options detailed previously, up to 11 years of reactor reloads could meet tritium demand and extend the tritium fuel need date to 2038-2041. This option assumes a levelized funding profile to minimize annual funding requests. Total cost for this option is estimated to be between \$6.1 billion and \$11.3 billion, excluding costs of using the uranium inventory options which could be an additional \$1.1 billion. A summary of the scenarios and results are shown in Table 11.

Table 11. AC100 Facility Cost Options

	Accelerated Base Case	Levelized Case Late Start
TPC Range (no operations)	\$3.1B - \$4.8B	\$6.1B-\$11.3B
Description of Case	Remobilization starts after only one year in warm standby	Lowest funding profile to meet a 2038 LEU need date
Max Annual Budget Request	\$860M	\$900M
Nominal Cash Flow		
Years in Standby (Warm/Cold/Demob)	1	7
1st Train begins production	2022	2035
First Reload Shipped	2023	2036
Project Start/End	2016-2025	2016-2038

The cash flow of each scenario is shown in Table 12, utilizing the high end of the cost estimate ranges. Should the U.S. Government decide to build an AC100 centrifuge national security plant, any of the scenarios above could be viable based on EU product delivery date requirements, funding profile preferences, and risk tolerances.

Table 12. Accelerated and Late Start Levelized Cash Flow Range for AC100 Facility



Other Infrastructure Needs

In addition to an enrichment facility capable of producing high-assay LEU and HEU, an unencumbered conversion facility that can convert high-assay LEU and HEU UF₆ gas to both

metal and oxide forms is required. The last facility in the United States that could convert high-assay UF_6 to an oxide form was located at the Nuclear Fuel Services site in Erwin, Tennessee and was decommissioned in the 1990s.

The Y-12 National Security Complex (Y-12) is currently the only U.S. facility that can convert high-assay EU oxide to a metallic form; however, Y-12 currently cannot process UF_6 gas coming from an enrichment facility. An additional logistical challenge is that there is not a designed and licensed container to enable shipping the high-assay UF_6 from an enrichment facility to a conversion facility. Such a container would have to be designed, tested, and fabricated by DOE/NNSA or a commercial entity, then licensed by the U.S. Department of Transportation prior to use.

The costs for these requirements have not been estimated and are not included in the estimates above.

VI. Conclusion

DOE/NNSA's defense and non-defense related missions require a reliable supply of Enriched Uranium (EU) in varying assays and forms to meet our defense and non-defense related missions. DOE/NNSA's current supply is limited and currently irreplaceable until decisions are made to address shortfalls in supply and production capability.

The most pressing defense mission need is for tritium. Alternate methods of producing tritium using different reactor types as well as accelerators were evaluated in the late 1990s as production options beyond the current program using CLWRs. In accordance with Congressional direction, these methods were re-evaluated in the Department's 2014 Tritium Production Future Technology Study synopsis in Section III of this report.²⁹ The results reaffirmed the Department's decision to produce tritium using irradiation services purchased through TVA. The study also re-validated the conclusions of a 1998 Congressional Budget Office assessment that stated other options would be more costly than the TVA option.³⁰

Production of tritium through purchase of irradiation services remains the current, most stable, and least costly option. The Department's current expectation to increase tritium production is to transition to the two-reactor option. TVA will continue to produce tritium in only one reactor until a second reactor is available for tritium production should the DOE/NNSA and TVA decide to implement the two-reactor case following appropriate review and completion of the CLWR SEIS.

The Tritium Readiness Program Baseline identifies sources of unobligated fuel for tritium production through 2027, assuming a second reactor comes online in the mid-2020s. The Department evaluated five options that can each provide a few years' worth of unobligated LEU fuel for tritium production. By combining existing baseline LEU and HEU fuel sources with some or all of these options, tritium production can be maintained through 2038-2041. There are costs, and some low to moderate risks, associated with down-blending these HEU sources.

Other defense missions will eventually require new sources of HEU by approximately 2060; for naval reactors by approximately 2060; to maintain the nuclear weapons stockpile; and, to support the Mutual Defense Agreement. Non-defense missions require high-assay LEU for isotope production and research reactor fuel, which is currently met by down-blending excess HEU. The excess HEU inventory set aside for these purposes is projected to be exhausted by around 2030. Installation of new scrap recovery capabilities could extend the supply by approximately eight to 10 years. While this fuel could potentially be supplied by commercial (domestic or foreign) producers, there are no current suppliers with the capability to enrich and convert high-assay LEU above 5 percent ²³⁵U.

²⁹ DOE, (U.S. Department of Energy), "Tritium Production Future Technology Study", Revision 0, April 2014

³⁰ Congressional Budget Office report, "Estimated Budgetary Effects of Alternatives for Producing Tritium," August 27, 1998, <http://www.cbo.gov/publication/11108>.

The United States lost the ability to enrich uranium using unrestricted technologies when the PGDP closed in 2013. To meet defense and non-defense mission requirements in the future, the United States will eventually need to reestablish an unrestricted uranium enrichment capability to produce unobligated EU when existing supplies run out. To that end, six uranium enrichment technologies that could be used to produce unobligated EU were evaluated against a standard set of criteria. Sufficient detail was provided to include rough order-of-magnitude costs for the most advanced technology to support decision-making on a path forward.

DOE/NNSA's Office of Nuclear Material Integration coordinated the development of this plan with significant input from the Offices of Defense Programs, Defense Nuclear Nonproliferation, Naval Reactors, Nuclear Energy, and Environmental Management. The Department will ensure the management of efforts to carry out these plans will be accomplished in the most efficient, effective, and expeditious manner.

Appendix A: References

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Appendix B: Congressional Language

This report was developed in response to the statutes and Congressional Reports and Appropriations Bills listed below.

Section 311 of Title III, Division D, of the Consolidated Appropriations Act, 2014 (Pub. L. 113-76).

(a) Not later than June 30, 2014, the Secretary shall submit to the Committees on Appropriations of the House of Representatives and the Senate a tritium and enriched uranium management plan that provides-

(1) an assessment of the national security demand for tritium and low and highly enriched uranium through 2060;

(2) a description of the Department of Energy's plan to provide adequate amounts of tritium and enriched uranium for national security purposes through 2060; and

(3) an analysis of planned and alternative technologies which are available to meet the supply needs for tritium and enriched uranium for national security purposes, including weapons dismantlement and down-blending.

(b) The analysis provided by (a)(3) shall include a detailed estimate of the near- and long-term costs to the Department of Energy should the Tennessee Valley Authority no longer be a viable tritium supplier.

Section 312(b) of Title III, Division D, of the Consolidated and Further Continuing Appropriations Act, 2015 (Public Law 113-235)

Section 312 (b) The Department shall provide a report to the Committees on Appropriations of the House of Representatives and the Senate not later than April 30, 2015 that includes:

(1) an accounting of the current and future availability of low-enriched uranium, highly-enriched uranium, and tritium to meet defense needs; and

(2) a cost-benefit analysis of each of the options available to supply enriched uranium for defense purposes, including a preliminary cost and schedule estimate to build a national security train."

House H.R. 4923 Energy and Water Development Appropriations Bill, 2015**• DOMESTIC URANIUM ENRICHMENT**

Domestic Uranium Enrichment provides research, development, operations, and maintenance funding to sustain the availability of low enriched uranium to support stockpile stewardship and other national security needs. The Committee recommends \$96,000,000 for Domestic Uranium Enrichment, \$34,000,000 above fiscal year 2014 and \$96,000,000 above the budget request.

The NNSA has concluded its project to demonstrate the technical viability of centrifuges with the United States Enrichment Corporation. Funding for Domestic Uranium Enrichment is provided to maintain those centrifuges in warm standby while the Department conducts further analysis of its tritium and enriched uranium centrifuges in fiscal year 2015. The Committee will consider further investments in domestic enriched uranium capabilities only after the Secretary of Energy and the Secretary of Defense conduct a bottoms-up interagency reevaluation of the active and reserve tritium stockpile requirements, and the Nuclear Weapons Council certifies to the Committees on Appropriations of the House of Representative and the Senate that the revalidated tritium stockpile amounts to be maintained by the Department of Energy represent the minimum active and reserve national security requirements. To ensure that the results of such analysis are available for consideration of the fiscal year 2016 budget request, the Nuclear Weapons Council should provide this certification to the Committees not later than March 1, 2015.

The NNSA is further directed to conduct an analysis of the process technologies available for providing enriched uranium, produce a conceptualized plant size for the options evaluated, and estimate the costs and time necessary for build-out of such plants. As part of this analysis, the NNSA shall include an option that represents the minimum train needed to produce LEU for anticipated tritium production needs, and compare the return on investment of additional acquisition costs needed to operate a full national security train at optimal efficiency. The NNSA shall provide the results of its analysis to the Committee on Appropriations of the House of Representatives and the Senate not later than June 1, 2015.

United States Enrichment Corporation Fund.—The Committee notes that despite the Government Accountability Office's May 2014 decision that the authorized uses of the United States Enrichment Corporation Fund (Fund) have been fulfilled, the Department is considering using approximately \$40,000,000 of the Fund to support domestic uranium enrichment capabilities through the end of fiscal year 2014. The Committee notes that the fiscal year 2014 Act made available transfer authority, which the Department has not utilized, to support these activities. The Committee recognizes that funding for domestic enrichment for defense purposes must be balanced against all other priorities and includes

discretionary appropriations for such activities. The recommendation includes a general provision that rescinds the remaining balances of the Fund.

S.R. 113-176 to accompany S. 2410 National Defense Authorization Act for Fiscal Year 2015

Procurement of unencumbered special nuclear material for tritium production

The committee directs the Secretary of Energy to determine if the Mutual Defense Agreement between the United Kingdom and Northern Ireland and the Government of the United States of America on the Uses of Atomic Energy for Mutual Purpose, dated July 5, 1958, permits the United States to obtain low enriched uranium for the purposes of tritium production or purchase directly tritium from the United Kingdom. Such a determination shall be due to the congressional defense committees no later than September 30, 2014

Senate Energy and Water Development Appropriations Bill, 2015

SEC. 309. (a) DOMESTIC URANIUM ENRICHMENT.—

None of the funds appropriated by this or any other Act or that may be available to the Department of Energy may be used to build a train of centrifuges using domestic enrichment technology for national security needs in fiscal year 2015.

Of the \$110,000,000 appropriated under “Weapons Activities” for domestic uranium enrichment, only \$55,000,000 shall be made available until the Secretary of Energy submits to the Appropriations Committees of the House and Senate—

- 1. an inventory of all unobligated enriched uranium available to the Department of Energy for defense purposes;*
- 2. an assessment of why the current inventory of available unobligated enriched uranium is not sufficient to meet defense needs;*
- 3. a cost-benefit analysis of each of the options available to supply enriched uranium for defense purposes, including new bilateral agreements; and*
- 4. if deemed necessary for national security needs, a determination by the Secretary of Energy that building a national security train is the lowest cost option that meets national security requirements.*

Appendix C: HEU Supply and Demand

This section can be made available to appropriately cleared parties upon request.

Appendix D: Tritium Supply and Demand

This section can be made available to appropriately cleared parties upon request.