United States Government Accountability Office

Report to Congressional Committees

February 2018

NUCLEAR WEAPONS

NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs and Improve Technology Cost Estimates

Accessible Version

GAO-18-126

GAO Highlights

Highlights of GAO-18-126, a report to congressional committees

Why GAO Did This Study

NNSA has several mission needs for enriched uranium, including providing LEU to fuel a nuclear reactor that produces tritium—a key isotope used in nuclear weapons. NNSA has a pressing defense need for unobligated LEU to fuel this reactor, meaning the uranium, technology and equipment used to produce the LEU, must be U.S. in origin. Because the United States lost its only source of unobligated LEU production in 2013, the supply is finite.

A House Armed Services Committee report included a provision for GAO to assess NNSA's plans to manage tritium and enriched uranium. This report examines (1) the actions NNSA is taking to extend its existing LEU inventories to address near-term tritium needs; (2) the extent to which NNSA's plan to analyze long-term options for supplying enriched uranium is consistent with DOE directives; and (3) NNSA's preliminary cost estimates for long-term uranium enrichment technology options and the extent to which they meet best practices for reliable estimates. GAO analyzed NNSA plans on costs, schedules, and risks; compared them with its guide on best practices in cost estimating; and interviewed NNSA and other officials.

What GAO Recommends

GAO is making two recommendations, including that NNSA revise the scope of its mission need statement and ensure that the scope of its cost estimates are aligned with the revised statement while developing estimates consistent with best practices. NNSA described actions planned and in process to address both recommendations.

View GAO-18-126. For more information, contact Allison Bawden at (202) 512-3841 or bawdena@gao.gov.

February 2018

NUCLEAR WEAPONS

NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs and Improve Technology Cost Estimates

What GAO Found

The National Nuclear Security Administration (NNSA), a separately organized agency within the Department of Energy (DOE), is taking or plans to take four actions to extend inventories of low-enriched uranium (LEU) that is unobligated, or carries no promises or peaceful use to foreign trade partners until about 2038 to 2041. Two of the actions involve preserving supplies of LEU, and the other two involve diluting highly enriched uranium (HEU) with lower enriched forms of uranium to produce LEU. GAO reviewed these actions and found the actual costs and schedules for those taken to date generally align with estimates. NNSA and GAO have identified risks associated with two of these actions. One of these risks has been resolved; NNSA is taking steps to mitigate another, while others, such as uncertainty of future appropriations, are unresolved.

NNSA's preliminary plan for analyzing options to supply unobligated enriched uranium in the long term is inconsistent with DOE directives for the acquisition of capital assets, which state that the mission need statement should be a clear and concise description of the gap between current capabilities and the mission need. The scope of the mission need statement that NNSA has developed can be interpreted to meet two different mission needs: (1) a need for enriched uranium for multiple national security needs, including tritium, and (2) a specific need for enriched uranium to produce tritium. The DOE directives also state that mission need should be independent of and not defined by a particular solution. However, NNSA is showing preference toward a particular solution—building a new uranium enrichment capability—and the agency has not included other technology options for analysis. Without (1) revising the scope of the mission need statement to clarify the mission need it seeks to achieve and (2) adjusting the range of options it considers in the analysis of alternatives process, NNSA may not consider all options to satisfy its mission need.

Although the scope of the mission need statement is unclear, NNSA has prepared preliminary cost estimates for the two uranium enrichment technology options—the large and small centrifuge—that the agency considers to be the most feasible. However, these estimates are limited in scope and do not fully meet best practices for reliable cost estimates. Based on GAO's review of NNSA documents, NNSA appears to favor an incremental approach to reestablishing an enrichment capability that could ultimately meet all national security needs for enriched uranium. The estimates' scope is limited, however, in that they reflect only the costs of the first increment—producing LEU for tritium—and do not reflect the full costs of building a uranium enrichment facility that could meet the range of enriched uranium needs. GAO's cost guide—which provides cost estimating best practices—states that the scope of preliminary cost estimates should reflect full life-cycle costs. Also, NNSA's estimates for the two options minimally or partially met best practice characteristics for reliable cost estimates even when assessed for the more limited mission scope. For example, the estimates excluded certain costs and did not describe the calculations used. NNSA officials said that the cost estimates are preliminary and will be revised. By developing reliable cost estimates that are aligned with the revised mission need statement and consistent with best practices, NNSA will reasonably ensure that it has reliable information to make a decision about which option to select.

Contents

Abbreviations

AVLIS	Atomic Vapor Laser Isotope Separation
CD	Critical Decision
DBOT	Downblending Offering for Tritium
DOD	Department of Defense
DOE	Department of Energy
EMIS	Electromagnetic Isotope Separation
GDP	Gaseous Diffusion Plant
GLE	Global Laser Enrichment
GMIS	Global Medical Isotope Systems
HEU	highly enriched uranium
LEU	low-enriched uranium
NNSA	National Nuclear Security Administration
ORNL	Oak Ridge National Laboratory
REU	Repurposed Excess Uranium
SILEX	Separation of Isotopes by Laser Excitation
State	Department of State
SWU	separative work unit
TPBAR	tritium-producing burnable absorber rod
TRL	Technology Readiness Level
TVA	Tennessee Valley Authority
USEC	USEC Inc.

441 G St. N.W.
Washington, DC 20548

February 16, 2018

The Honorable John McCain
Chairman
The Honorable Jack Reed
Ranking Member
Committee on Armed Services
United States Senate

The Honorable Mac Thornberry
Chairman
The Honorable Adam Smith
Ranking Member
Committee on Armed Services
House of Representatives

The National Nuclear Security Administration (NNSA), a separately organized agency within the Department of Energy (DOE), is responsible for the management and security of the nation's nuclear weapons, as well as nonproliferation programs and the Naval Nuclear Propulsion program, which supports reactor design and production for the U.S. nuclear-powered naval fleet. Uranium, at various levels of enrichment, is important for the achievement of all of these missions.[1] Specifically, NNSA has identified several national security and other needs for enriched uranium, including: (1) producing tritium which is a necessary component of nuclear weapons,[2] through an existing process in a Tennessee Valley Authority (TVA)[3] reactor that uses low enriched uranium (LEU) as fuel; (2) supplying highly enriched uranium (HEU) to meet the U.S. Navy's needs for its nuclear powered aircraft carriers and

[1]Uranium is categorized by concentration of the isotope uranium-235, expressed as a percentage "assay." Natural uranium must be enriched to increase its assay to the level required for a certain purpose. Low enriched uranium, which is typically used in commercial nuclear reactors, has an assay of 3 to 5 percent uranium-235. Highly enriched uranium generally has an assay level of at least 90 percent.

[2]Tritium is a radioactive isotope of hydrogen. Isotopes are varieties of a given chemical element with the same number of protons but different numbers of neutrons. Tritium has both military and commercial applications. Its most significant national security use is as a component in the triggering mechanism in nuclear weapons. Its commercial uses include self-luminescent devices, such as exit signs in buildings and airplane dials.

[3]TVA is a federal electric utility and the nation's largest public power company. TVA operates three nuclear plants—Browns Ferry, Sequoyah, and Watts Bar.

submarines; and (3) providing "high assay" LEU for medical isotope production and research reactor fuel. According to DOE, only unobligated uranium can be used to achieve NNSA's national security missions. All uranium is considered unobligated when neither the uranium nor the technology or equipment used to enrich it carries an "obligation" to a foreign country. These obligations are established under international agreements that describe the conditions for civilian nuclear cooperation between the United States and foreign partners. Uranium or uranium-related technology subject to peaceful-use obligations under such agreements cannot be used for military purposes by the United States. The United States lost its sole supplier of unobligated enrichment services when the last operating enrichment plant using U.S. technology ceased enriching uranium in May 2013.[4] As a result, NNSA's supply of unobligated LEU is finite and becoming increasingly scarce. In May 2014, NNSA projected that its inventory of unobligated LEU fuel for tritium production would last through 2027.[5]

In 2014 and 2015, Congress required NNSA to submit analyses of its options to meet tritium and enriched uranium needs for national security purposes. In October 2015, NNSA released its *Tritium and Enriched Uranium Management Plan Through 2060*, which presented several actions—along with their projected costs, schedules, and risks—to extend its existing inventories of enriched uranium to address its near-term need for tritium.[6] In addition, NNSA identified technical and other options to ensure an adequate long term supply of tritium and enriched uranium in support of national security and other needs.

The House Armed Services Committee report accompanying H.R. 4909, a bill for the National Defense Authorization Act for Fiscal Year 2017 included a provision for GAO to assess NNSA's October 2015 plan and subsequent actions to manage tritium and enriched uranium. This report examines: (1) the actions NNSA is taking to extend its existing inventories

[4]The Paducah Gaseous Diffusion Plant, in Paducah, Kentucky was constructed and began enriching uranium in the 1950s and ceased operations in 2013 because of high production costs coupled with a global drop in demand for enrichment services.

[5]Department of Energy, National Nuclear Security Administration, *Tritium Readiness Subprogram Tritium Production Fuel Supply Plan* (May 2014).

[6]NNSA is also required to submit a plan for meeting national security requirements for unencumbered (unobligated) uranium through 2065 to the congressional defense committees in every even-numbered year ending in 2026. The next plan is due to Congress by December 31, 2018. 50 U.S.C. § 2538c (2018).

of enriched uranium to address near term tritium needs and the costs, schedules, and risks of those actions; (2) the extent to which NNSA's plan to analyze options for supplying enriched uranium in the long term is consistent with DOE directives; and (3) NNSA's preliminary cost estimates for long-term uranium enrichment technology options and the extent to which they meet best practices for reliable estimates.

To address all three objectives, we analyzed NNSA planning documents—as well as other key agency strategies and implementation plans—and interviewed officials from NNSA and DOE, the Department of Defense (DOD), the Department of State (State), TVA, and private companies that play a role in the production of enriched uranium. We also visited DOE's Oak Ridge National Laboratory (ORNL), where work continues on uranium enrichment technology; NNSA's Y-12 National Security Complex in Tennessee, which is involved in the management of enriched uranium; and the American Centrifuge demonstration plant in Ohio, where an advanced uranium enrichment technology was in development until 2016, to understand the technical and policy issues that affect the current LEU inventory and that may affect the future supply of unobligated LEU.

To examine the actions that NNSA is taking to extend its existing inventories of enriched uranium to address its near-term tritium needs and the costs, schedules, and risks of those actions, we reviewed agency documents pertaining to these actions. We also obtained and analyzed NNSA information on actual costs and schedules for each action, where available, and compared that information against estimated costs and schedules. We identified risks associated with each action by reviewing NNSA documentation and interviewing NNSA and TVA officials and a representative of a private company involved in the actions.

To examine the extent to which NNSA's plan to analyze options for supplying enriched uranium in the long term is consistent with DOE directives, we reviewed NNSA and ORNL documentation and interviewed federal officials from NNSA and the State Department as well as ORNL and NNSA contractor representatives regarding efforts NNSA has taken to identify potential options and preliminarily assess their feasibility. We evaluated NNSA's plan against DOE directives, such as DOE Order 413.3B *Program and Project Management for the Acquisition of Capital Assets* and associated guidance, such as G 413.3-4A *Technology Readiness Assessment Guide*, and G 413.3-17 *Mission Need Statement Guide*.

To examine NNSA's preliminary cost estimates for long-term uranium enrichment technology options and the extent to which they meet best practices for reliable estimates, we reviewed NNSA and contractor planning, analysis, and cost documents. We compared the information in those documents to GAO's Cost Estimating and Assessment Guide (cost guide), which is a compilation of best practices for federal cost estimating organizations and industry to use, develop, and maintain reliable cost estimates throughout the life of an acquisition program.[7] According to the cost guide, reliable cost estimates feature four characteristics—comprehensive, well-documented, accurate, and credible. These best practices apply to cost estimates throughout a project's life cycle, including early, rough-order-of-magnitude estimates developed at or before project initiation. We interviewed an NNSA official and a representative from the contractor who prepared the preliminary cost estimates about their methodologies and the results that were used to support the preliminary cost estimates. We assessed the information we gathered against best practices and shared our preliminary analysis with NNSA officials to obtain their perspectives and identify reasons for any observed shortfalls compared with cost-estimating best practices. We reviewed their comments and any additional information they provided and incorporated them to finalize our assessment. See appendix I for additional information on our objectives, scope, and methodology.

We conducted this performance audit from August 2016 to February 2018 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[7] *GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs (Supersedes GAO-07-1134SP),* GAO-09-3SP (Washington, D.C.: Mar. 2, 2009).

Background

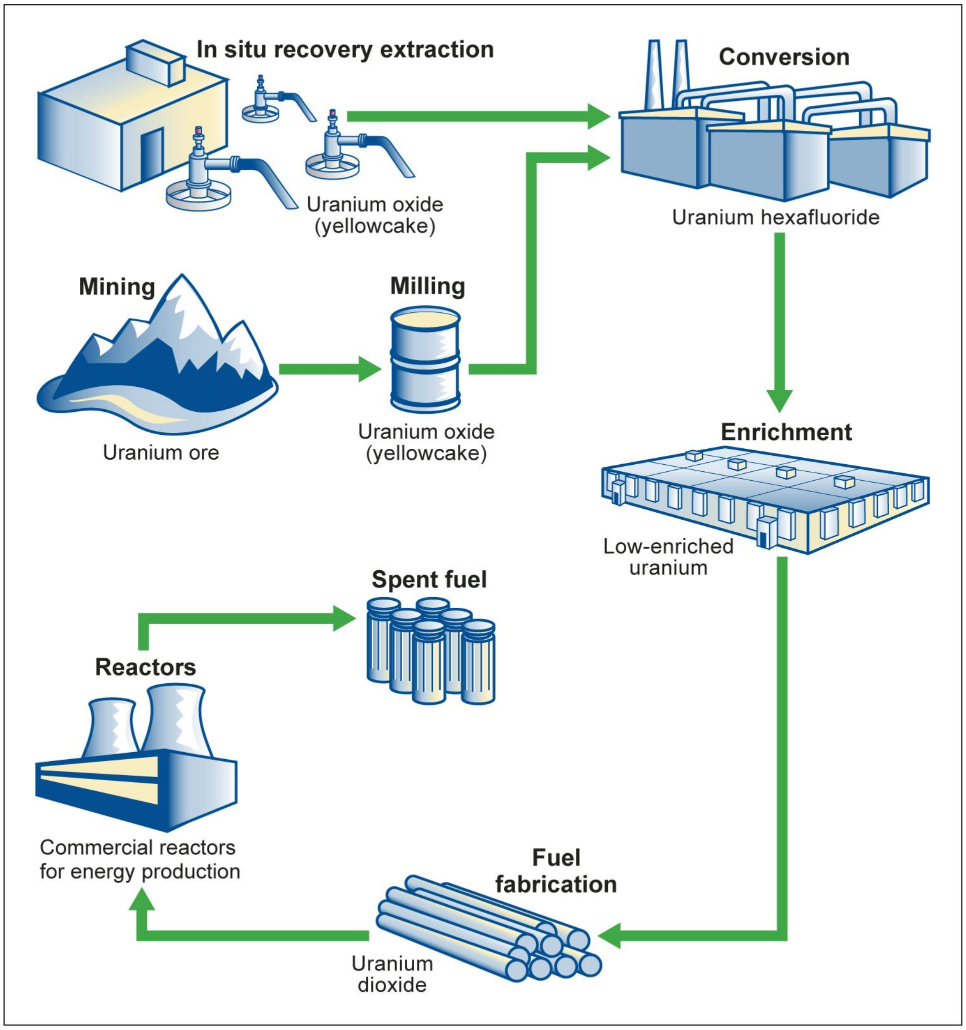
Nuclear Fuel Production and Uranium Enrichment Technologies

Uranium is a naturally occurring radioactive element that is enriched to fuel nuclear power plants and that can also be used to meet certain national security purposes. Natural uranium is comprised of approximately 99.3 percent of the uranium-238 isotope and 0.7 percent of the uranium-235 isotope—which undergoes fission to release energy. Uranium enrichment is the process of increasing the concentration of uranium-235 in a quantity of natural uranium to make LEU to fuel nuclear power plants, or to make HEU, which is used in nuclear weapons and as fuel by the U.S. Navy. Generally, to produce enriched uranium, uranium is extracted or mined from underground deposits, converted from a solid to a gas, enriched to increase its concentration of uranium-235, and then fabricated into fuel elements, such as rods for commercial nuclear reactors, appropriate for their ultimate use. These steps make up the nuclear fuel cycle (see fig. 1).[8] After the fuel has been irradiated in a nuclear power reactor, it is considered "spent" nuclear fuel. Spent fuel can be chemically reprocessed, and the enriched uranium recycled for reuse. The United States used to reprocess spent nuclear fuel but has not done so since the mid-1970s, primarily to discourage other countries from pursuing reprocessing because of concerns over nuclear proliferation, as we have previously reported.[9] Currently, in the United States, spent fuel is stored as waste.

[8]We have also reported on an infrequently used means of obtaining LEU by re-enriching depleted uranium tails, a product of enrichment, that is usually treated as waste and has a concentration of uranium-235 lower than that of natural uranium. When depleted uranium tails are re-enriched, the initial stages of the fuel cycle—extraction through conversion—are skipped. See GAO, *Department of Energy: Enhanced Transparency Could Clarify Costs, Market Impact, Risk, and Legal Authority to Conduct Future Uranium Transactions,* GAO-14-291 (Washington, D.C.: May 9, 2014).

[9]In 2006, DOE announced its intention to reconsider reprocessing spent fuel. Specifically, DOE proposed building multibillion-dollar nuclear facilities to demonstrate advanced reprocessing and recycling technologies that could significantly reduce waste, as well as reduce proliferation risks. Congress eliminated funding for this program in 2009. For additional information on the nonproliferation risks of reprocessing spent fuel, see GAO, *Nuclear Fuel Cycle Options: DOE Needs to Enhance Planning for Technology Assessment and Collaboration with Industry and Other Countries,* GAO-12-70 (Washington, D.C.: Oct. 17, 2011).

Figure 1: Nuclear Fuel Cycle



Sources: GAO analysis of International Atomic Energy Agency, Nuclear Regulatory Commission, Congressional Research Service, Department of Energy, and Tennessee Valley Authority documents. | GAO-18-126

LEU can also be produced by downblending HEU to LEU. This involves mixing HEU with a “diluent” or other forms of uranium—such as natural uranium—to reduce the concentration of the uranium-235 isotope in the uranium and produce an overall lower level of enrichment.

Until 2013, uranium was enriched in the United States both for national security and commercial purposes. Beginning in the 1940s, DOE and its predecessor agencies provided uranium enrichment services—first for national security purposes and later for the emerging commercial nuclear power industry—using government-owned gaseous diffusion plants. In

1992, the U.S. government established the United States Enrichment Corporation (USEC) as a government corporation to take over operations of DOE's enrichment facilities and to provide uranium enrichment services for the U.S. government and utilities that operate nuclear power plants.[10] In 1998, the corporation was privatized under the USEC Privatization Act. From 1998 until 2013, DOE relied exclusively on USEC to obtain enrichment services for the production of LEU needed to produce tritium. In May 2013, USEC ceased enrichment at its last commercially active enrichment plant in Paducah, Kentucky, which it had leased from DOE since the time of USEC's establishment. USEC has been the only company to enrich uranium with U.S. technology.

Gas centrifuge technology, rather than gaseous diffusion technology, is currently used around the world to enrich uranium. Gas centrifuges work by spinning uranium hexafluoride in a gas form inside a centrifuge rotor at an extremely high speed.[11] The rotation creates a strong centrifugal force, which separates the lighter uranium-235 molecules from the heavier uranium-238 molecules. The enrichment achieved by a single gas centrifuge is not sufficient to achieve the desired assay, so a series of centrifuges are connected together in a configuration called a cascade. In the United States, URENCO—a European enrichment consortium—operates a gas centrifuge enrichment plant in New Mexico.[12]

The obligations governing the use of foreign uranium enrichment technology and nuclear material in the United States are established under international agreements between the United States and foreign partners.[13] These agreements generally impose certain terms and conditions on transfers of nuclear material and equipment, including, among other things, requiring peaceful use of the material and

[10]The corporation was initially established as the United States Enrichment Corporation. Upon privatization, the United States Enrichment Corporation became a subsidiary of the newly created USEC Inc.

[11]The rotors in centrifuge cylinders can spin at 1,500 revolutions per second or 90,000 rotations per minute.

[12]This facility is owned and operated by Louisiana Energy Services, a subsidiary of URENCO, which is a consortium of companies owned or controlled by the British and Dutch governments and by two German utilities.

[13]Partners include individual countries, the International Atomic Energy Agency, the European Atomic Energy Community, and Taiwan. The parties to the agreement with Taiwan are the American Institute in Taiwan and the Taipei Economic and Cultural Representative Office in the United States.

equipment. The agreements' peaceful-use provisions generally state that material, equipment, and components subject to the agreements will not be used for any nuclear explosive device, for research on or development of any nuclear explosive device, or for any military purposes.

National Security and Other Uses for Enriched Uranium

This section discusses national security and other uses for enriched uranium, such as tritium production, highly enriched uranium, and high-assay low enriched uranium.

Tritium Production

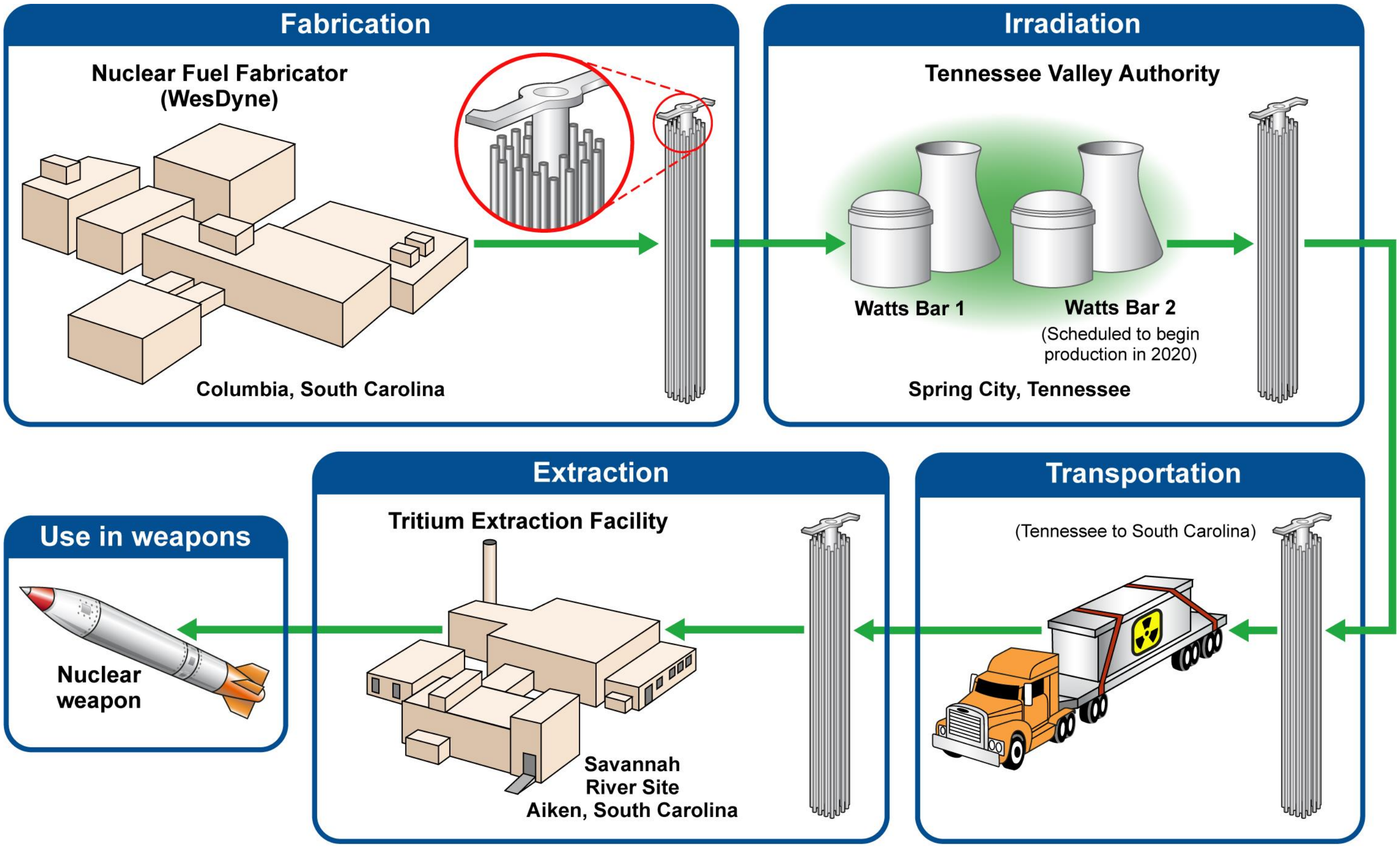
Tritium is a key isotope used in nuclear weapons. NNSA needs an assured source of tritium to maintain the capabilities of the nuclear stockpile and has called tritium a "pressing" defense need.[14] However, tritium has a relatively short half-life of 12.3 years and decays at a rate of about 5.5 percent per year.[15] It must be periodically replenished to maintain the designed capability of the weapons. Some tritium may be recycled from dismantled weapons, but the inventory must also be replenished through the production of new tritium.

At present, NNSA produces tritium through the use of one of TVA's electricity-producing nuclear reactors fueled with unobligated LEU. Small quantities of tritium are the normal by-products of electricity-producing nuclear power plants, such as those owned and operated by TVA. To produce more tritium than usual and later collect it, specially designed targets—called tritium-producing burnable absorber rods (TPBAR)—are loaded with the unobligated LEU and irradiated in TVA's Watts Bar 1 reactor. Irradiated TPBARs are unloaded during normal fuel reloading and shipped to NNSA's Tritium Extraction Facility at the Savannah River Site in South Carolina. There the tritium is extracted and prepared for use in nuclear warheads and bombs (see fig. 2 for NNSA's tritium production process).

[14]National Nuclear Security Administration, *Tritium and Enriched Uranium Management Plan Through 2060* (Washington, D.C.: Oct. 2015).

[15]As a result of the 5.5 percent radioactive rate of decay, an amount of tritium will decrease by about 11 percent in 2 years, 25 percent in 5 years, and 50 percent in 12.3 years.

Figure 2: National Nuclear Security Administration's Tritium Production Process



Source: GAO analysis of National Nuclear Security Administration materials. | GAO-18-126

Prior to the use of TVA's reactor, the United States used other government-owned reactors to produce tritium (see sidebar). In 1999, TVA signed an interagency agreement with DOE to produce tritium at its Watts Bar and Sequoyah commercial nuclear reactors.[16] Since 2003, TVA has been producing tritium for NNSA at its Watts Bar 1 reactor. TVA does not have plans to use the Sequoyah reactors for tritium production in the near term, according to a TVA document.

[16]DOE's Interagency Agreement with TVA to produce tritium is in effect until November 30, 2035. Under the agreement, DOE is to pay TVA approximately $1.5 billion for its costs to produce tritium over the 35-year term.

History of U.S. Tritium Production

From 1954 until 1988, the United States produced the majority of its tritium using nuclear reactors at the Savannah River Site in South Carolina. Smaller amounts of tritium were also produced using nuclear reactors at the Department of Energy's (DOE) Hanford Site in Washington. When the site's last operating reactor—known as K Reactor—was shut down due to safety concerns in 1988, the United States lost its capability to produce tritium for the nuclear weapons stockpile.

In 1998, the Secretary of Energy announced that DOE would turn to commercial light water reactors as the sole means of meeting the future demand for tritium. From 1988 to 1998, DOE was able to meet its tritium requirements by harvesting and recycling it from dismantled nuclear warheads, as the United States decreased the size of its nuclear arsenal. However, because of tritium's short half-life, DOE could not meet its long-term tritium needs in this manner indefinitely. Since 2003, the Tennessee Valley Authority (TVA) has been producing tritium for National Nuclear Security Administration (NNSA) at its Watts Bar 1 commercial nuclear power reactor.

Source: GAO analysis of DOE, NNSA, and TVA documents; DOE (top photo); TVA (bottom photo). | GAO-18-126

The amount of tritium that NNSA needs changes based on national security requirements. In fiscal year 2015, NNSA conducted a review of the tritium inventory and anticipated future demand. At that time, NNSA determined that to meet future tritium demand a second TVA reactor would be required to irradiate TPBARs and produce additional tritium. Using a second TVA reactor would increase the amount of unobligated LEU needed for tritium production using this process, according to NNSA documents.

Highly Enriched Uranium

NNSA also supplies HEU for national security and other missions. NNSA provides HEU to fuel reactors for the U.S. Navy's aircraft carriers and submarines. NNSA recovers HEU from excess dismantled nuclear weapons. According to NNSA's October 2015 plan, HEU from these sources will meet naval reactors' demand through 2060. After this time, NNSA will need additional sources of HEU for naval nuclear reactors. To satisfy non-defense demands, NNSA also supplies HEU to, among other things, fuel research reactors for medical isotope production and other research applications.

High-Assay Low Enriched Uranium

NNSA's nonproliferation mission requires "high assay" LEU—meaning LEU enriched in the uranium-235 isotope to below 20 percent but above the standard 3 to 5 percent used in most commercial reactors—for research and isotope production reactor fuel. Since there are no commercial uranium enrichment facilities licensed to produce high-assay LEU, it must be produced by downblending HEU. According to NNSA documents, the HEU inventory allocated for research and isotope production reactors using high-assay LEU is projected to be exhausted by around 2030. After this time, a new supply of high-assay LEU for research and isotope production reactors will need to be identified.

DOE Project Management

NNSA has initiated a process to determine a long-term solution for obtaining enriched uranium and tritium. DOE's Order 413.3B, *Program and Project Management for the Acquisition of Capital Assets*, governs how NNSA acquires capital assets with total project costs greater than $50 million, which could include a new uranium enrichment capability or other new capability to produce tritium.[17] The stated goal of the order is to deliver fully capable projects within the planned cost, schedule, and performance baseline.

Order 413.3B also establishes DOE's critical decision (CD) process.[18] This process divides the capital asset acquisition into five project phases that progress from a broad statement of mission need, to requirements that guide project execution, through design and construction, and concludes with an operational facility. Each phase ends with a major approval milestone—or "critical decision"—that marks the successful completion of that phase.

A key activity during CD-0, the preconceptual design phase is the preparation of a mission need statement. A mission need statement identifies the capability gap between the current state of a program's mission and the mission plan. DOE's Order 413.3B provides direction for preparing a mission need statement, including that it be independent of a particular solution, and that it should not be defined by equipment, facility, technological solution, or physical end-item. This approach is to allow the agency the flexibility to explore a variety of approaches and not prematurely limit potential solutions.

Under Order 413.3B, an analysis and selection of alternatives—which builds off the mission need—should be conducted during the CD-1 phase,

[17]DOE defines capital assets as land, structures, equipment, and intellectual property, which are used by the federal government and have an estimated useful life of 2 years or more.

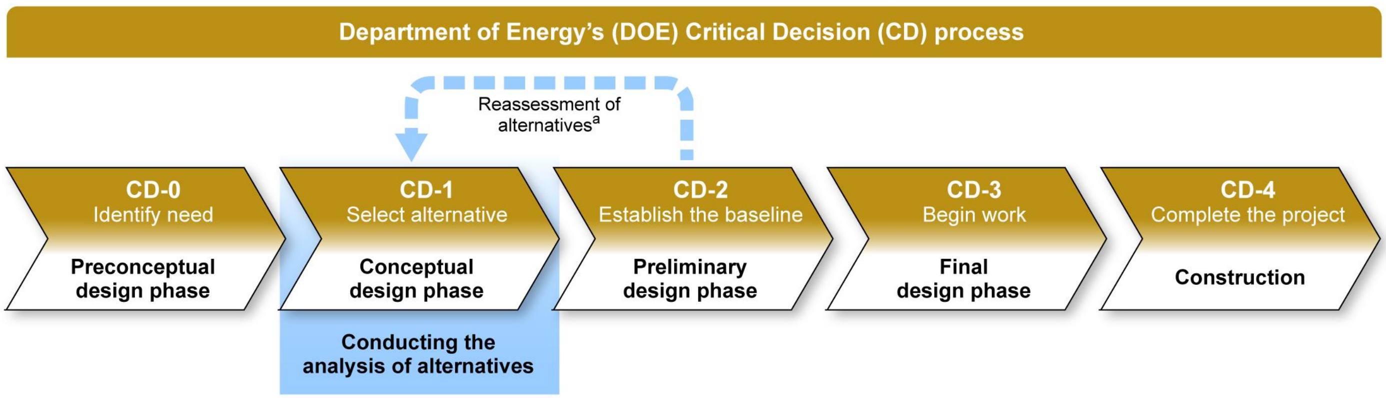
[18]Department of Energy, *Program and Project Management for the Acquisition of Capital Assets*, Order 413.3B, Chg. 4 (Washington, D.C.: Oct. 13, 2017).

the conceptual design phase.[19] In addition to the requirements of Order 413.3B, DOE has guidance for identifying, analyzing, and selecting alternatives that is found throughout the seven guides associated with the order.[20] Conducting the analysis of alternatives is a key first step to help ensure that the selected alternative best meets the agency's mission need and that this alternative is chosen on the basis of selection criteria, such as safety, cost, or schedule. Figure 3 illustrates when DOE conducts the analysis of alternatives as part of its project management process for capital asset projects.

[19]In September 2009, we defined this process as an analytical study that is intended to compare the operational effectiveness, costs, and risks of a number of potential alternatives to address valid needs and shortfalls in operational capability. See GAO, *Defense Acquisitions: Many Analyses of Alternatives Have Not Provided a Robust Assessment of Weapon System Options,* GAO-09-665 (Washington, D.C.: Sept. 24, 2009).

[20]Guidance for conducting an analysis of alternatives is included in the following documents: Department of Energy, *Mission Need Statement Guide,* G 413.3-17 (Washington, D.C.: Oct. 22, 2015); *U.S. Department of Energy Acquisition Strategy Guide for Capital Asset Projects,* G 413.3-13 (Washington, D.C.: July 22, 2008); *U.S. Department of Energy Project Review Guide for Capital Asset Projects,* G 413.3-9 (Washington, D.C.: Sept. 23, 2008); *Managing Design and Construction Using Systems Engineering for Use with DOE Order 413.3A,* G 413.3-1 (Washington, D.C.: Sept. 23, 2008); *Cost Estimating Guide,* G 413.3-21 (Washington, D.C.: May 9, 2011); *Performance Baseline Guide,* G 413.3-5A (Washington, D.C.: Sept. 23, 2011); and *Integrated Project Team: Guide for Formation and Implementation,* G 413.3-18A (Washington, D.C.: Feb. 3, 2012).

Figure 3: Conducting the Analysis of Alternatives as Part of the Department of Energy's Project Management Process for Capital Asset Projects



[a]If the top end of the approved CD-1 cost range grows by more than 50%, the program office must conduct another analysis of alternatives and obtain a new CD-1 approval.

Source: GAO analysis of DOE's Order 413.3B. | GAO-18-126

In October 2016, NNSA approved a mission need statement for long-term capability to supply unobligated enriched uranium for tritium production and presented a preliminary set of options to meet that need.[21] In December 2016, DOE approved CD-0 to begin the acquisition of such a capability. Consistent with direction in DOE Order 413.3B, NNSA has begun conducting an analysis of alternatives that is to identify the option that would best meet the mission need for a domestic uranium enrichment capability. In August 2017, DOE and NNSA officials stated that the analysis of alternatives will be completed by the end of 2019.

Also, under DOE Order 413.3B, DOE's technology readiness levels (TRL) are incorporated into the CD process. TRLs are used by federal agencies and industry to assess the maturity of evolving technologies. TRLs are measured along a scale of 1 to 9, beginning with TRL 1 (or basic principles observed and reported) and ending with TRL 9 (or actual system operated over the full range of expected mission conditions). DOE guidance states that a TRL of 4—system or component validation at laboratory scale—is recommended for CD-1 (conceptual design process). Projects are encouraged to achieve a TRL of 7—full scale demonstration of a prototypical system in a relevant environment—prior to CD-3 (final design phase).

[21]Department of Energy, Office of Domestic Uranium Enrichment, *Domestic Uranium Enrichment Mission Need Statement CD-0* (Washington, D.C.: October 2016).

Best Practices for Project Cost Estimating

In March 2009, we issued our cost guide to provide assistance to federal agencies with preparing cost estimates, among other things.[22] Drawing from federal cost estimating organizations and industry, the cost guide describes best practices for ensuring development of high-quality—that is, reliable—cost estimates. A reliable cost estimate helps ensure that management is given the information it needs to make informed decisions. The cost guide identifies four characteristics of a reliable cost estimate: (1) comprehensive, (2) well documented, (3) accurate, and (4) credible. DOE's Order 413.3B states, among other things, that its cost estimates shall be developed, maintained, and documented in a manner consistent with methods and best practices identified in our cost guide, DOE guidance, and applicable acquisition regulations and Office of Management and Budget guidance.

Our cost guide can be used to evaluate the reliability of rough-order-of-magnitude estimates. Rough-order-of-magnitude estimates are typically used to support "what-if" analyses and are helpful in examining initial differences in alternatives to identify which are most feasible. However, the nature of a rough-order-of-magnitude estimate means that it is not as robust as a detailed, budget-quality, life-cycle estimate and, according to the guide, its results should not be considered or used with the same level of confidence. Further, the cost guide states that because this estimate is developed from limited data and in a short time, it should never be considered a budget-quality cost estimate.

NNSA Is Taking or Plans to Take Four Actions to Extend Existing Inventories of Enriched Uranium to Address its Near-term Tritium Needs

NNSA is taking or plans to take four actions to extend its existing inventories of unobligated enriched uranium to address its near-term need for tritium and has generally identified the costs, schedules, and risks for these actions. These actions would together extend the supply of unobligated LEU from 2027 until approximately 2038 to 2041, according

[22] GAO-09-3SP.

to NNSA documents. NNSA first identified the actions to extend its unobligated LEU supply based on an analysis completed by the DOE Uranium Inventory Working Group, which was convened by NNSA in September 2014 to analyze the department's uranium inventory and identify material and options to provide unobligated LEU for tritium production reactors.[23] These actions were later presented in NNSA's October 2015 plan.[24]

Of the four actions NNSA is taking or plans to take, two actions involve nuclear material accounting practices that help preserve supplies of unobligated LEU, and two of the actions involve downblending HEU.[25] NNSA has generally identified the costs and schedules for these actions. Specifically, NNSA estimated in its October 2015 plan that the total cost of the four actions would be approximately $1.1 billion from fiscal years 2016 through 2025 and would provide additional quantities of unobligated LEU for TVA to meet NNSA's tritium needs through 2038 to 2041. Based on our review, the actual costs and schedules through October 2017 generally align with the estimates in NNSA's October 2015 plan. NNSA and GAO have identified some risks associated with two of these actions. One of these risks has been resolved; NNSA is taking steps to mitigate another; while other risks, such as the uncertainty of future appropriations, are unresolved.

The following are the four actions, and their costs, schedules, and risks.

[23]The Uranium Inventory Working Group assessed all sources of uranium within DOE and NNSA mission areas, including defense programs, naval reactors, nonproliferation, and environmental management. The group coordinated with TVA to identify options that each provides a few years' worth of unobligated LEU for tritium production.

[24]National Nuclear Security Administration, *Tritium and Enriched Uranium Management Plan Through 2060* (Washington, D.C.: Oct. 2015). This report was prepared in response to congressional direction from several sources, including: the Consolidated Appropriations Act, 2014, Pub. L. No. 113-76, § 311, 128 Stat. 5, 175; and Consolidated and Further Continuing Appropriations Act, 2015, Pub. L. No. 113-235, § 312(b), 128 Stat. 2130, 2326.

[25]According to NNSA documents, the HEU from retired weapons that is being downblended is unobligated since the material itself and the technology used to enrich it are U.S.-origin and not subject to peaceful-use provisions.

Book Storage of TVA LEU

Book storage is an industry-wide nuclear material accounting practice, where a nuclear material supplier—such as a uranium enrichment plant or nuclear fuel fabricator—can record in its accounts, or books, the amount of enriched uranium in its inventory belonging to a customer, such as a nuclear power plant operator, and hold that material for future delivery to the customer. TVA has entered into contracts with two nuclear fuel suppliers to conduct book storage to preserve unobligated LEU for TVA on behalf of NNSA. This practice effectively parks the unobligated LEU into a separate account so that the material is not inadvertently loaded into a non-tritium producing reactor. Book storage helps TVA preserve limited quantities of unobligated LEU for the future; it will eventually be used for tritium production at the Watts Bar reactor. According to agency officials, a key benefit of using book storage for LEU is that TVA does not have to physically store the material. According to these officials, book storage is significantly less expensive than paying to set up a physical storage facility.

The terms of TVA's book storage contracts, including the parties involved, schedules, and values, are proprietary and business sensitive, according to TVA officials. Based on our analysis, the actual fees paid by TVA under its book storage contracts align with NNSA's projected costs for book storage in its October 2015 plan. NNSA is reimbursing TVA for the book storage fees it is paying. According to NNSA, the obligations preserved from using book storage for unobligated LEU through these contracts extend the LEU fuel need date by 3 years. NNSA's October 2015 plan did not identify any specific risks for these existing book storage contracts.

Obligation Exchanges of LEU

Obligation exchanges are another industry-wide nuclear material accounting practice, which involves the transfer of obligations on nuclear material—such as LEU—between two entities without physically moving the material.[26] Similar to book storage, TVA may conduct obligation exchanges on behalf of NNSA to increase the inventory of unobligated LEU available for tritium production. According to NNSA's October 2015 plan, TVA may conduct additional obligation exchanges in the future on behalf of NNSA. According to NNSA and TVA officials, at least one future obligation exchange is anticipated but has not been scheduled. According to these officials, there are no specific costs associated with transferring the obligations on LEU between entities. In addition, if additional inventories of unobligated LEU are identified, NNSA officials told us they will encourage TVA to conduct additional obligation exchanges to preserve the material. NNSA's October 2015 plan did not identify any specific risks for obligation exchanges.

Repurposed Excess Uranium (REU) Downblending

NNSA's first downblending action involves downblending 10.4 metric tons of HEU that was previously declared excess to national security needs.[27] NNSA initiated the 3-year REU program in 2015 and, according to NNSA officials, the last shipment of HEU for downblending is expected in December 2018. According to these officials, close-out and final operations of the contract will end in early 2019. The REU downblending is being performed through a contract between NNSA and WesDyne, which subcontracts with another company, Nuclear Fuel Services, according to DOE documents we reviewed and officials we interviewed.[28]

[26]For example, Facility A may have a certain amount of LEU physically located on its site, all of which is obligated. Facility B may have an equal amount of LEU physically located on its site, all of which is unobligated. In an obligation exchange between the two facilities, rather than Facility A physically transferring a portion of its obligated LEU to Facility B in exchange for the same amount of unobligated LEU, the two facilities can exchange the obligations on the material in their material records, so that each facility now has a portion of obligated and a portion of unobligated LEU. Following an obligation exchange, each facility will have the same total amount of LEU as it had before the exchange, but the conditions on the use of the material will have changed. For additional information, see GAO, *Nuclear Material: Agencies Have Sound Procedures for Managing Exchanges but Could Improve Inventory Monitoring,* GAO-16-713 (Washington, D.C.: Sept. 23, 2016).

[27]Before the REU program, over the last 2 decades, DOE has been down-blending HEU from excess weapons declarations through the HEU Disposition Program. These activities have produced fuel for U.S. commercial power plants and for research reactors in the United States and around the world.

[28]Nuclear Fuel Services, a subsidiary of BWX Technologies, Inc., operates the only downblending plant in the United States.

According to NNSA documents, NNSA is the sole customer for this downblending effort. The estimated costs for the REU downblending program are $373 million, according to NNSA's October 2015 plan. According to NNSA and contractor officials, the fixed price of the contract is $333.8 million, and the invoiced costs for the REU downblending program through October 2017 are $141.4 million, which aligns with the terms of the contract.[29] According to an NNSA official, NNSA is paying for the REU program through a combination of funds provided through annual appropriations and what the parties refer to as a "barter" arrangement, according to NNSA officials and documents.[30] Under this arrangement, NNSA is compensating the downblending contractor by transferring title of the derived LEU to WesDyne, which will be retained as unobligated LEU and eventually sold to TVA for tritium production purposes.[31] The REU downblending program will generate approximately five reactor reloads of unobligated fuel for TVA, and will likely be used in the early to mid-2030s, according to NNSA documents.

Regarding the risks for the REU program, NNSA identified the uncertainty of whether NNSA would be able to continue to conduct barters of derived LEU to pay for downblending services. For example, the 2015 plan notes that, while such transactions had worked well for previous downblending campaigns, declining markets values for enriched uranium in recent years had reduced industry's interest in being compensated for services with a portion of the derived LEU. In addition, NNSA officials identified a lawsuit challenging the legality of barters as a risk. This suit was dismissed in July 2016. As a result, this specific risk no longer affects the Department,[32] and according to NNSA officials, the agency anticipates being able to

[29]Under a firm-fixed-price contract, the contractor assumes most of the cost risk; by accepting responsibility for completing a specified amount of work for a fixed price, the contractor earns a profit if the total costs it incurs in performing the contract are less than the contract price but loses money if its total costs exceed the contract price.

[30]We have reviewed uranium transactions characterized as barters by DOE and have instead found them to be sales through an agent. GAO, *Department of Energy—December 2004 Agreement with the United States Enrichment* Corporation, B-307137, (Washington, D.C.: July 12, 2006); GAO, *Excess Uranium Inventories: Clarifying DOE's Disposition Options Could Help Avoid Further Legal Violations*, GAO-11-846, (Washington, D.C.: Sept. 26, 2011).

[31]NNSA is currently planning to transfer all of the LEU derived from downblending to WesDyne. However, if market conditions change, NNSA may not transfer all of the LEU, according to NNSA officials.

[32]We have identified an additional concern regarding barters. Specifically, on two occasions, we have found that transactions characterized by DOE as barters were in fact

continue compensating Nuclear Fuel Services with derived LEU for the duration of the REU program.

Downblending Offering for Tritium (DBOT)

NNSA's second downblending action, which is planned to begin in 2019, will involve HEU mainly composed of undesirable scrap, primarily in the form of oxides, left over from uranium processing activities. NNSA estimates that the planned DBOT program will generate approximately 10 reloads of unobligated fuel for TVA, likely to be used in the mid-2030s. According to an NNSA document, the program is expected to run for a 6-year period from 2019 through 2025. However, the schedule for HEU downblending under the DBOT action has not yet been finalized. According to NNSA officials, as of January 2018 the agreement is still being negotiated, but NNSA officials told us they anticipate that TVA will manage Nuclear Fuel Services' down-blending activities in support of the DBOT program as well as the resulting unobligated LEU and its associated flags. NNSA's estimated costs for the DBOT downblending program are $770 million, according to NNSA's October 2015 plan.[33] NNSA plans to pay for the DBOT program solely with funds provided through annual appropriations. NNSA does not currently plan to transfer any LEU resulting from this downblending program as payment to the contractor and will instead keep all the LEU for future tritium production.

The DBOT program has not been initiated, so we could not assess whether the program's actual costs and schedule align with the estimates in NNSA's October 2015 plan. However, NNSA officials said they have confidence in the projected costs for the DBOT program since the estimates are based on previous downblending programs that NNSA has conducted over the past decade.

sales through an agent, and that DOE's treatment of the sales proceeds violated the miscellaneous receipts statute. See GAO *Excess Uranium Inventories: Clarifying DOE's Disposition Options Could Help Avoid Further Legal Violations,* GAO-11-846 (Washington, D.C.: Sept. 26, 2011). See GAO, *Department of Energy: December 2004 Agreement with the United States Enrichment Corporation,* B-307137 (Washington, D.C.: July 12, 2006).

[33]According to NNSA officials, the agency will own the LEU from the DBOT program and may choose to sell it to TVA or give it to TVA to offset required payments for tritium production. In that way, some of the $770 million will be recoverable by the federal government, less cost of money and storage costs, based on the market price for LEU at that time.

NNSA identified two risks, and we identified one additional risk, facing the DBOT program. First, NNSA's October 2015 plan identified the uncertainty of annual appropriations in the amount of $770 million to support this program. In addition, NNSA's October 2015 plan identified a second risk associated with the availability of material for the DBOT program. The DBOT material will consist largely of scrap oxide left over from weapons production processes, some to be generated in future years. Because the schedules for those processes may change, the amounts of material available for DBOT and the dates when it will be available are subject to some uncertainty. Furthermore, we identified an additional risk to the DBOT program that is not addressed in NNSA's October 2015 plan. Specifically, NNSA did not indicate which nuclear fuel cycle company would be used for the book storage of the LEU resulting from the DBOT program, and there is no guarantee that a company would be willing to engage in book storage for NNSA. A senior NNSA official stated that this detail will be worked out once the DBOT contract is finalized. NNSA and TVA officials noted that other fuel cycle facilities have previously been uninterested in conducting book storage for NNSA, so options may be limited. According to NNSA officials, if book storage was unavailable in the future, NNSA could pay for the physical storage of the LEU for the DBOT program. Since the costs of physically storing LEU for the DBOT program are not included in NNSA's cost estimates, this could increase the overall costs of the program.

NNSA's Preliminary Plan to Analyze Options to Supply Enriched Uranium in the Long Term is Inconsistent with DOE Directives

NNSA's preliminary plan—as outlined in its domestic uranium enrichment mission need statement—to analyze options for supplying enriched uranium in the long term is inconsistent with DOE directives. This is because the scope of the mission need statement can be interpreted to fulfill multiple mission needs, which is inconsistent with DOE directives that such a statement should be a clear and concise description of the gap between current capabilities and the mission need. Under either interpretation of the mission need statement, NNSA is not complying with these directives because it is showing preference toward a particular solution—building a new uranium enrichment capability—and the agency has not included other options for analysis. In the mission need statement, NNSA has preliminarily identified two uranium enrichment technologies as the most feasible options for reestablishing a uranium enrichment capability, but both face deployment challenges.

NNSA's Domestic Uranium Mission Need Statement Can Be Interpreted to Fulfill Multiple Mission Needs, Making it Inconsistent with DOE Directives

NNSA's preliminary plan—as outlined in its domestic uranium enrichment mission need statement—for analyzing options to supply enriched uranium in the long term is unclear because the scope of the mission need statement can be interpreted to fulfill more than one mission need, and this is inconsistent with DOE directives. Specifically, NNSA's October 2016 mission need statement—developed by NNSA's Office of Domestic Uranium Enrichment—identified two mission needs: (1) a need for enriched uranium for a range of national security and other missions, including LEU for tritium production, HEU for the U.S. Navy, and high-assay LEU for research needs; and (2) a specific need for tritium. Because the mission need is not clearly stated, it is not clear whether NNSA intends to identify a future source of enriched uranium that could meet a range of mission needs, or only meet the specific mission need for tritium. According to DOE guidance for the mission need statement, the mission need statement should be a clear and concise description of the gap between current capabilities and the mission need. A senior NNSA official acknowledged that the mission need statement was ambiguously written because there are a range of mission needs for enriched uranium, and the ultimate mission need that the analysis of alternatives process will meet is unclear. Under either interpretation of the intent of the mission need statement, the document does not fully comply with DOE directives. According to DOE Order 413.3B, the mission need should be independent of a particular solution and should not be defined by the equipment, facility, technological solution, or physical end-item. This approach allows the Office of Domestic Uranium Enrichment the flexibility to explore a variety of solutions and not limit potential solutions.

Under the first interpretation of NNSA's mission need statement (which appears to be its preferred interpretation, according to NNSA documents), NNSA needs a future source of enriched uranium for a range of missions—initially LEU to produce tritium, but later also to produce high-assay LEU for research needs and HEU for the U.S. Navy. Specifically, the document states that if the United States decided to reestablish a domestic uranium enrichment capability, it "could meet several national security missions." Further, it states that "future demand for additional enrichment assays and volumes should be considered in the selection of the enrichment capacity to meet national security needs."[34] This suggests that NNSA may be missing opportunities to consider options for providing additional enriched uranium that do not entail reestablishing a uranium enrichment plant.

For example, while the mission need statement discusses some policy options that would provide NNSA with a new source of enriched uranium without building a new enrichment capability, it excludes at least one policy option that was originally identified in NNSA's October 2015 plan—reprocessing DOE-owned spent nuclear fuel to recover HEU (which could also be downblended to produce LEU). Reprocessing spent nuclear fuel could provide a significant quantity of enriched uranium without the need for a new enrichment capability. It is not clear why NNSA excluded this option from the mission need statement at this early point in the development of alternatives. See appendix II for a discussion of other options NNSA includes in its mission need statement that could provide NNSA with a new source of enriched uranium without building a new enrichment capability.

Under the second, narrower interpretation of the mission need statement, NNSA would need to obtain LEU solely to meet its mission need for tritium. However, contrary to DOE directives that a mission need statement be independent of a particular solution and not be defined by equipment, facility, technological solution, or physical end-item, NNSA is showing preference for a particular end-item—enriched uranium—to continue the tritium production mission. The mission need statement indicates a preference for using enriched uranium to continue the tritium production mission, as it only identifies options to obtain additional enriched uranium. This approach would exclude consideration of certain technology options, such as one that may have the potential to produce tritium without the need for enriched uranium. Specifically, during our review, we identified a technology capable of producing tritium that does not require enriched uranium and is being developed by Global Medical Isotope Systems (GMIS).[35] This technology was not included in NNSA's mission need statement as an option to help NNSA meet its tritium

[34]Department of Energy, Office of Domestic Uranium Enrichment, *Domestic Uranium Enrichment Mission Need Statement CD-0*, (Washington, D.C.: October 2016).

[35]GMIS provides isotopes and production technology for medical, industrial, and security applications.

production requirements. An NNSA office separate from the Office of Domestic Uranium Enrichment—the Office of Nuclear Materials Integration—has funded the GMIS technology in a demonstration effort to determine whether it can produce tritium in sufficient quantities to support NNSA's needs.[36]

The GMIS technology is currently at a low TRL, and the tritium production estimates have not been independently verified, but a senior NNSA official and GMIS representatives told us that it produced "appreciable amounts of tritium" during the demonstration.[37] However, another senior NNSA official stated that it would be more appropriate to consider the GMIS technology in a process being conducted by another NNSA office—the Tritium Sustainment Office—which is currently examining potential options to meet tritium needs in 2055 and beyond, when TVA's Watts Bar reactors may no longer be operating.[38] This official, however, told us that the program office has no plans to update its last technology evaluation from 2014, which did not include consideration of the GMIS technology.[39] If the purpose of NNSA's mission need statement is to meet tritium requirements, then NNSA may be missing the opportunity to assess a technology that could meet the mission need without the need for enriched uranium. Without revising the scope of the mission need statement to clarify which mission need it seeks to achieve and adjusting, as appropriate, the range of preliminary options being considered in the analysis of alternatives, NNSA may not consider all options that could satisfy its ultimate mission need.

[36]Based on the results of the initial demonstration phase, NNSA intends to fund a second phase of research beginning in late 2017 during which NNSA and GMIS would engage several national laboratories to independently validate the results of the technology. According to a senior NNSA official, as of January 2018, they were waiting for the final testing results.

[37]NNSA officials noted that tritium measurements for the GMIS technology have not yet been independently confirmed.

[38]TVA's licenses to operate Watts Bar 1 and Watts Bar 2 expire in 2035 and 2055, respectively. If tritium production will be needed beyond 2055, TVA would need to apply for license renewals with the Nuclear Regulatory Commission. It is uncertain whether the commission would approve license extensions beyond 2055, according to NNSA officials.

[39]National Nuclear Security Administration, *Tritium Readiness Subprogram: Tritium Production Future Study*, April 2014.

NNSA Has Identified Two Uranium Enrichment Technologies as Most Feasible for Reestablishing a Uranium Enrichment Capability, but Both Face Challenges

The mission need statement identifies six potential enrichment technology options for reestablishing an unobligated uranium enrichment capability. The technology selected could be used first to produce LEU to support the tritium production mission, and potentially later used to produce high-assay LEU for research needs and HEU for the U.S. Navy, according to NNSA documents. According to NNSA's mission need statement, these six technologies were identified by a team of federal, national laboratory, and contractor experts in uranium enrichment technologies in December 2014, later presented in the October 2015 plan, and then included in the mission need statement.

Among the six technologies, four—restart of the Paducah Gaseous Diffusion Plant, electromagnetic isotope separation, atomic vapor laser isotope separation, and separation of isotopes by laser excitation—are unlikely to be feasible, according to NNSA documents (app. III provides additional information on these four enrichment technologies). Some of these technologies have produced enriched uranium in the past, but extraordinary technical or financial barriers, past research failures, or peaceful-use restrictions would likely preclude further consideration by NNSA, according to NNSA documents.

According to NNSA documents, NNSA has preliminarily identified the two remaining uranium enrichment technologies as the most feasible options to supply unobligated LEU for tritium production: the AC100 ("large") centrifuge and a "small" centrifuge design. However, both of these options face challenges to deployment.

AC100 Centrifuge

Of the identified options, the AC100, or large centrifuge, is the technology that is furthest along in development. Centrus Energy Corp.—the private company known as USEC Inc. prior to its bankruptcy in 2014—developed a large (about 40 feet tall) advanced centrifuge for uranium enrichment.[40] From June 2012 through September 2015, DOE invested approximately $397 million to financially support a research, development, and demonstration program for the large centrifuge technology at Centrus' demonstration facility—the American Centrifuge Plant—in Ohio (See fig. 4).[41] However, in September 2015, DOE announced that it would not continue funding the demonstration plant in Ohio past the end of that month. According to a September 2015 DOE memorandum, the department had obtained the testing data it needed and determined that there was "minimal incremental value" in continuing demonstration operations.[42] Centrus was unable to continue operation of the demonstration plant without further government support and, in February 2016, announced its intent to demobilize it. Appendix IV provides additional information on the development of Centrus' AC100 large centrifuge technology.

[40]In September 2014, following Chapter 11 bankruptcy proceedings, USEC Inc. changed its name to Centrus Energy Corp.

[41]DOE signed a $350 million cooperative agreement with USEC in June 2012 through April 2014. As part of this agreement, DOE provided $280 million, or 80 percent, of the costs for the program, and USEC provided the remaining 20 percent. From May 2014 through the end of September 2015, DOE provided an additional $117 million in funding.

[42]Department of Energy, Memorandum for the Secretary from Frank G. Klotz, September 8, 2015.

Figure 4: Large Centrifuges for Uranium Enrichment at the American Centrifuge Plant

Source: Centrus Energy Corp. | GAO-18-126

According to NNSA's October 2015 report, at the conclusion of DOE's support, Centrus had successfully demonstrated that the large centrifuge technology had achieved a TRL of 7 to 8—or the generally successful demonstration of a test facility. DOE has continued funding, at a lower level, Centrus' further development of the large centrifuge technology at a test facility in Oak Ridge, Tennessee, through September 2018. The October 2016 mission need statement estimated that it would take 2 to 5 years to complete development of the technology. According to a senior DOE official, though DOE has discontinued the majority of its funding, the department has taken two actions to preserve the large centrifuge technology—preserving the intellectual property for this technology and hiring some former Centrus employees—to ensure that the technology can be deployed if it is selected in the analysis of alternatives.

However, we identified several challenges that could complicate future efforts to deploy the large centrifuge technology—challenges related to the preservation of intellectual property, royalty costs for commercial deployment, and the weakening of Centrus' U.S. supplier and knowledge base.

Intellectual property. A senior DOE official stated that there were two issues with DOE's Office of Nuclear Energy original preservation of the information. First, preservation of the schematics began before certain technical issues with the demonstration plant were discovered, and consequently, Centrus' proposed resolution of those issues was not included in the documentation, according to DOE and NNSA officials. Second, a DOE official and Centrus representatives stated that DOE's contract with Centrus did not specify how the schematics were to be preserved. Rather than preserving the schematics in an electronic engineering format, Centrus preserved them in a different format that will require them to be reconstructed in an engineering program, according to the DOE official. NNSA officials acknowledged there were issues with the 2014 preservation effort and stated that negotiations were under way to contract with Centrus for a second preservation effort that would include updated schematics in the correct format and the documentation on the proposed resolution of the technical issues.

Royalty costs. Although DOE owns the intellectual property, by agreement, Centrus is owed royalties if the large centrifuge technology is deployed for commercial purposes. According to a June 2002 agreement between DOE and USEC, these royalties would be capped at $665 million. In a January 2017 request for information from industry, NNSA expressed interest in obtaining enriched uranium through a federal government-private industry partnership. In January 2017, NNSA officials said that they were not sure how royalties might affect such a partnership. It is possible that if a private industry partner was only interested in producing enriched uranium for the government alongside a commercial operation, the royalties could discourage such a partnership, or that some of the costs might be passed on to the government. However, the royalties may be less than the cost of developing a new enrichment capability, so such an arrangement may also attract partners interested in entering the market but not in developing new technology.

Supplier base. Centrus representatives told us that Centrus assembled an extensive domestic supplier base during the demonstration program to show that enrichment services could be unobligated. According to Centrus representatives and a Centrus document, the company had sourced components for the demonstration plant from over 900 different suppliers and manufacturers in 28 states, and that following its closure, many of these companies would go out of business or lose the capability to produce the necessary parts. As a result, if the large centrifuge option is selected, a domestic supplier base will have to be rebuilt, according to Centrus representatives. NNSA officials acknowledged that—as NNSA conducts the analysis of alternatives process—Centrus' supplier and manufacturing base will continue to diminish.

Knowledge base. Centrus representatives have raised concerns that the closure of the American Centrifuge Plant and associated layoffs of qualified workers may make it difficult to re-hire experienced centrifuge workers in the future. According to a cost estimate review prepared by a contractor for NNSA, the American Centrifuge Plant employed 370 full-time equivalent workers during the demonstration program. However, as of January 2017, it employed approximately 117 staff, according to a Centrus document. NNSA officials acknowledged that the loss of skilled workers is a concern and stated that, as a mitigating measure, ORNL has hired knowledgeable former Centrus personnel for further centrifuge research projects at ORNL.

Small Centrifuge

The second most feasible option to supply unobligated LEU for tritium production is the design for a small centrifuge technology. NNSA is funding an experiment to develop a centrifuge design that it anticipates will be smaller (from 6 to 14 feet tall), simpler, and potentially less expensive to build and maintain than the large centrifuge, according to an NNSA document. The experiment began at ORNL in 2016 and is based on prior ORNL experience with centrifuges. According to NNSA and ORNL documents, the small centrifuge experiment will take 3.5 years to achieve a TRL of 3 to 4—successful validation at laboratory scale—and cost approximately $42 million for this validation effort. During our visit to ORNL in December 2016, laboratory representatives told us that prototypes had not yet been constructed and showed us their preliminary design work and initial construction of their facility. As of December 2017, the first prototype of three or four planned sizes had been built and tested, according to NNSA officials and ORNL representatives. Following completion of the experiment, the mission need statement estimates that it could take another 4 to 7 years to bring the technology to a TRL of 9 (ready to deploy).

Like the large centrifuge technology, the small centrifuge technology faces challenges that could complicate its deployment. For example, according to NNSA officials and ORNL representatives, the small centrifuge experiment is on an aggressive testing schedule to demonstrate results and potential scalability to meet NNSA's planned 2019 deadline to select a preferred alternative in the analysis of alternatives process. Further, according to NNSA officials and ORNL representatives, if the small centrifuge design is selected, ORNL would not build and operate the plant because it is focused on research and development. Instead, NNSA would have to identify and contract with another entity to license, transfer, and deploy the technology, according to NNSA officials and ORNL representatives. NNSA officials also stated that there will be challenges in establishing a U.S. manufacturing base of suppliers for the small centrifuge and associated equipment.

NNSA's Preliminary Cost Estimates for the Most Feasible Uranium Enrichment Technologies Are Limited in Scope and Do Not Fully Meet Best Practices

Though the scope of the mission need statement is unclear, NNSA has prepared preliminary cost estimates for the two uranium technologies it considers most feasible: the large and small centrifuge. These estimates are limited in scope and the estimate for the large centrifuge was premised on assumptions that were no longer valid. In addition, even when assessed for a more limited scope—producing LEU for tritium—the cost estimates do not fully meet best practices for reliable estimates applicable to all cost estimates.

NNSA's Preliminary Cost Estimates for the Uranium Enrichment Technologies it Considers Most Feasible Are Limited in Scope, and One Is Premised on Invalid Assumptions

Though the scope of the mission need statement is unclear, NNSA's preliminary cost estimates for the two uranium technologies it considers most feasible—the large and small centrifuge—are limited in scope, and the estimate for the large centrifuge was premised on assumptions that were no longer valid. Specifically, the limited scope of the cost estimates mean that they do not reflect the full costs of building a uranium enrichment facility that could eventually provide the capacity to enrich enough uranium to meet multiple needs, not just tritium. As previously noted, NNSA identified two mission needs: (1) a need for enriched uranium for a range of national security and other missions, including LEU for tritium production, HEU for the U.S. Navy, and high-assay LEU for research needs; and (2) a specific need for tritium.

According to DOE and NNSA documents and NNSA officials, NNSA appears to favor an incremental approach to reestablishing a domestic uranium enrichment capability. This incremental approach would start with the selection of an enrichment technology in an enrichment plant capable of meeting tritium production requirements but could be expanded to meet the other governmental enriched uranium needs over time, according to our review of NNSA documents.[43] Best practices for cost estimating state that programs following such an approach should clearly define the characteristics of each increment of capability so that a rigorous life cycle cost estimate can be developed.[44] In addition, we have recommended that agencies conducting incremental acquisitions consider establishing each increment of increased capability with its own

[43]For example, an April 2014 DOE analysis of domestic enrichment technologies stated that the HEU needs may be met with an incremental expansion of the enrichment capacity. In addition, an August 2015 DOE memo states that NNSA would need to begin construction on the additional HEU capacity as soon as production of the LEU capacity is complete.

[44]GAO-09-3SP.

cost and schedule baseline.[45] However, the scope of NNSA's cost estimates for the large and small centrifuges are limited only to an enrichment plant capable of meeting the tritium production requirements, according to DOE and NNSA documents. The cost estimates do not estimate the incremental costs of the additional enrichment capacity necessary to meet additional enriched uranium needs such as HEU. NNSA officials stated that the cost estimates were preliminary in nature and that they anticipate developing more in-depth cost estimates as NNSA progresses further in the analysis of alternatives process. By limiting the scope of the cost estimates to one mission need—LEU for tritium—and not addressing the additional costs to meet other enriched uranium mission needs, NNSA's cost estimates may be underestimating the life cycle costs of the technology options under evaluation—which could lead the agency to select a less cost-effective technology option.

We also found that NNSA relied on a Centrus-provided scenario for the large centrifuge cost estimate that was premised on assumptions that were no longer valid, rather than using a scenario that more accurately reflected conditions at the demonstration plant at the time of the analysis. We found that the large centrifuge cost estimate had not been substantially updated since fall 2014. According to DOE documents, NNSA officials, and Centrus representatives, the estimate was originally prepared by Centrus in the fall of 2014, and NNSA and its contractor made minimal updates to this estimate in January 2015 and again in fall 2016. However, this meant that NNSA officials used a scenario that assumed conditions that were no longer accurate as of October 2016, the date of the mission need statement.

This scenario, for example, assumed that the demonstration plant would be left intact for 5 years—in a cold standby state—followed by a restart of operations. However, in February 2016, Centrus had already publicly announced that it would begin decontamination and decommissioning the demonstration plant in spring 2016. An alternate scenario—complete demobilization of the demonstration plant followed by a restart of operations after 10 years—may have more closely reflected conditions at

[45]GAO, *Tactical Aircraft: F-22A Modernization Program Faces Cost, Technical, and Sustainment Risks,* GAO-12-447 (Washington, D.C.: May 2, 2012). We assessed DOD's F-22A modernization program against DOD policy and found that tracking and accounting for the full and accurate cost of each modernization increment, and individual projects within each increment, were limited by the way the modernization program had been structured, funded, and executed. DOD implemented our recommendation by managing additional modernization increments as separate acquisition programs.

the time. According to a December 2014 estimate provided by Centrus to DOE and NNSA, this scenario presented the most risk, as it meant that the site, staff, and supplier base would all have to be reconstituted after a significant break—which could be very difficult. According to this estimate, the cost of the alternate scenario would likely be $2.6 billion greater. NNSA officials stated that they had used the scenario that they thought best fit the conditions at the time, and Centrus officials agreed that cold standby was an appropriate scenario to use. However, by using the cold standby scenario rather than the demobilization scenario, NNSA appears to have underestimated the costs to build an enrichment facility by several billion dollars. A senior NNSA official noted that, for the large centrifuge, they intend to create a new estimate that does not rely on Centrus.

NNSA's Preliminary Cost Estimates for the Uranium Enrichment Technologies it Considers Most Feasible Do Not Fully Meet Best Practices for Reliable Estimates

Even when assessed for a more limited scope—producing LEU for tritium—NNSA's preliminary cost estimates for the two uranium enrichment technology options that the agency considers to be the most feasible—the large and small centrifuge technologies—do not fully meet best practices for reliable cost estimates, including those for early stages of acquisition. Our cost guide—which presents best practices for cost estimates—states that high-quality, or reliable, cost estimates—including preliminary and rough-order-of-magnitude estimates—must meet four characteristics: they must be comprehensive, well-documented, accurate, and credible.[46] DOE Order 413.3B states that cost estimates must be developed, maintained, and documented in a manner consistent with the methods and best practices identified in, among other things, our cost guide. Reliable cost estimates are crucial tools for decision makers, according to best practices. According to the cost guide best practices, cost estimates are considered reliable if each of the four characteristics is substantially or fully met. If any of the characteristics is not met, minimally met, or partially met, then the estimates cannot be considered to be reliable. Office of Management and Budget guidance notes the importance of reliable cost estimates at the early stages of project initiation, stating that early emphasis on cost estimating during the

[46]GAO-09-3SP.

planning phase is critical to successful life cycle management—in short, determining whether benefits outweigh costs.

NNSA's mission need statement presented rough-order-of-magnitude cost estimates of $7.5 to $14 billion to build a national security enrichment plant using the large centrifuge technology, and an estimate of $3.8 to $8.3 billion to build such a plant using the small centrifuge technology. We found that the large centrifuge cost estimate only partially met the characteristics of being comprehensive and credible, and minimally met the characteristics of being well-documented and accurate. The small centrifuge cost estimate only partially met the characteristic of being comprehensive, and minimally met the characteristics of being well-documented, accurate, and credible. Because the large and small centrifuge cost estimates do not fully meet the best practices characteristics of reliable cost estimates, we concluded that they are not reliable. We shared our assessments with NNSA officials and a representative from an NNSA contractor and discussed the findings. We reviewed their comments and any additional information they provided and incorporated them to finalize our assessments. NNSA officials explained that the cost estimates are preliminary and are intended only to be rough-order-of-magnitude estimates since the process is only in the early stages and will be revised as the analysis of alternatives process moves forward. NNSA officials stated that they are aware of the limitations of the preliminary large and small centrifuge cost estimates. By developing reliable cost estimates consistent with best practices, NNSA will reasonably ensure that it has reliable information to make an informed decision about its options. The following is a summary of our assessments.

- **Comprehensive.** Best practices state that—to be considered comprehensive—a cost estimate should include both government and contractor costs of the project over its full life cycle, from "cradle to grave." This includes costs from the inception of the project through design, development, deployment, and operation and maintenance, to retirement of the project. A life cycle cost estimate can support budgetary decisions, key decision points, milestone reviews, and investment decisions. DOE Order 413.3B does not specifically require a life cycle cost estimate at CD-0. Nonetheless, according to best practices, having a complete life cycle cost estimate helps ensure that all costs are fully accounted for and that resources are efficiently allocated to support the project.

  We found that the cost estimate to build a large centrifuge facility partially met the comprehensive characteristic because it included a high-level description of the work to be performed, and presented a brief summary description of the schedule, number of machines, and activities. However, the estimate was not a life cycle cost estimate because it excluded certain costs, such as retirement and close-out costs. In addition, other than noting a government oversight fee, the documentation does not specify whether the estimated costs are government or contractor costs. The estimate contains a 17 percent add-on, which an NNSA contractor told us accounts for DOE and contractor oversight costs, but the estimate does not specify how those costs are allocated.[47]

We found that the cost estimate to build a small centrifuge facility also partially met the comprehensive characteristic. We found that the estimate included costs for manufacturing, design, testing of the centrifuges, and 11 years of operations but, similar to the large centrifuge facility estimate, did not include retirement and close-out costs.

- **Well-documented.** Best practices state that data are the foundation of every cost estimate and that the quality of the data affects an estimate's overall credibility. Thus, the supporting documentation for an estimate should capture in writing the source data used, an assessment of the reliability of the data, and how the data were normalized to make them consistent with and comparable to other data used in the estimate.[48] The documentation should describe in sufficient detail the calculations performed and the estimating methodology used to derive each project element's cost such that any cost analyst could understand what was done and replicate it. Without good documentation, management may not be convinced that the estimate is credible; supporting data will not be available for creating a historical database; questions about the approach or data used to create the estimate cannot be answered; lessons learned and a history for tracking why costs changed cannot be recorded; and the scope of the analysis cannot be thoroughly defined.

  We found that the cost estimate to build a large centrifuge facility minimally met this characteristic. NNSA's contractor adjusted estimates previously provided by Centrus for inflation and added an

[47]NNSA's cost estimates were prepared by a third party contractor.

[48]Data are normalized in several ways. One example is normalizing cost units for inflation. Because the cost of an item has a time value, it is important to know the year in which funds were spent. For example, an item that cost $100 in 1990 is more expensive than an item that cost $100 in 2005 because of the effects of inflation over the 15 years that would make the 1990 item more expensive when converted to a 2005 equivalent cost.

estimate for DOE's oversight and fees. The documentation does not provide any of the supporting cost data or include descriptions of adjustments or normalization made to the data. We found that the estimate's supporting documentation does not provide a description of the specific calculations and presents methodologies in only broad terms. The documentation does not describe the steps taken to develop the estimates and does not provide enough information or supporting data to enable an analyst unfamiliar with the program to replicate the cost estimates. We were unable to trace the calculations to assess the accuracy and suitability of the methodology.

Similarly, we found the cost estimate to build a small centrifuge facility minimally met this characteristic. We found that the supporting documentation does not include information about the supporting data underlying the cost estimate. The sources of the data are not documented, and no information is included about how the data were normalized to make them comparable to other data used in the estimate. We found that it would be difficult to recreate this estimate because no supporting data or electronic cost models were documented.

- **Accurate.** According to best practices, a cost estimate should provide results that are unbiased; that is, the estimate should not be overly conservative or optimistic. An estimate is accurate when, among other things, it is based on an assessment of most likely costs, adjusted properly for inflation, and contains few, if any, mathematical mistakes. Best practices state that unless an estimate is based on an assessment of the most likely costs and reflects the degree of uncertainty given all of the risks considered, management will not be able to make good decisions.[49] Not adequately addressing risk, especially risk that is outside the estimator's control or that were never conceived to be possible, can result in point estimates that give decision makers no information about their likelihood of success or give them meaningless confidence intervals.

  We found the cost estimate to build a large centrifuge facility minimally met this characteristic. We could not determine whether the estimate is unbiased because no risk and uncertainty analysis had been performed. Portions of the work breakdown structure's elements are based on historical costs, but neither the historical data were provided, nor was there a thorough description of how those historical

[49]GAO-09-3SP.

costs were adjusted or used.[50] The contractor applied a 2 percent inflation factor but did not document the source of this factor; a representative of NNSA's contractor stated that another DOE office recommended using that factor. We found no mathematical mistakes in the overall calculations, but the model was not available to evaluate the methodologies used.

For the small centrifuge, we found the cost estimate minimally met this characteristic. We found that no risk or uncertainty analysis had been performed. The estimate uses a 2.4 percent inflation factor, but there is no documentation about the origin of this factor. An independent cost review performed by DOE's Office of Project Management Oversight and Assessments stated that this inflation factor was overly optimistic and recommended the use of a 4 percent factor. We did not detect any mathematical errors in the overall calculations, but the model was not available to evaluate the methodologies.

- **Credible.** The credible characteristic reflects the extent to which a cost estimate can be trusted, according to our cost guide.[51] For example, to be considered credible, the cost estimate should include a sensitivity analysis that examines how changes to key assumptions, parameters, and inputs affect the estimate. This analysis helps ensure that a range of possible costs are identified, as well as risks and their effects that may affect those costs. In addition, major cost elements should be cross-checked by the estimator to validate the results, and an independent cost estimate should be conducted by an outside group. The absence of a sensitivity analysis increases the chance that decisions will be made without a clear understanding of the impacts on costs, and the estimate will lose credibility.

  The cost estimate to build a large centrifuge facility partially meets this characteristic. NNSA presents several case studies rather than conducting a sensitivity analysis. These case studies only differ in one key assumption—schedule—but do not differ in any other major assumptions. The cost estimate documentation identified some major cost elements as cost drivers, but no cross-check information had

[50]A work breakdown structure is a necessary program management tool because it provides a basic framework for a variety of related activities such as estimating costs, developing schedules, identifying resources, determining where risk may occur, and providing the means for measuring program status.

[51]GAO-09-3SP.

been documented. DOE performed cross-checks in an independent cost review.

The cost estimate to build a small centrifuge facility minimally meets this characteristic. There is no evidence in the supporting documentation that a sensitivity analysis was completed. Some programmatic risks were identified in the documentation. No cross-check information had been documented. DOE performed an independent cost review which adjusted the project management cost to make it consistent with the large centrifuge project management cost estimate.

Regarding the large centrifuge, an NNSA official said that the agency had requested the supporting documentation that formed the basis of the estimate Centrus prepared in 2014, but that Centrus did not provide the information, stating that it was proprietary. However, according to Centrus representatives, Centrus offered to provide updated cost estimates and supporting data—provided that they were appropriately protected—but NNSA declined the offer. According to an NNSA official, the agency has not made a renewed effort to obtain this information because Centrus is still a publicly-traded company that would like to commercialize the large centrifuge technology.

Regarding the small centrifuge, an NNSA official told us that the agency did not have sufficient data to create a reliable preliminary cost estimate because the small centrifuge experiment is still in the preliminary design and development stages. In the absence of such data, ORNL based its estimate on its decades-long expertise and experience with centrifuges, as well as on the cost structure of the large centrifuge, according to NNSA documents. NNSA and DOE officials stated that they expect to have data by mid-2019 that would support a reliable cost estimate for inclusion in the analysis of alternatives process, which is expected to conclude in 2019. The officials said that they are still developing the technology and intend to create a new cost estimate.

Conclusions

Tritium is a key isotope used in U.S. nuclear weapons, and the United States requires an ongoing supply of tritium to sustain the nuclear stockpile. Since 2013, the United States has not had a supplier of unobligated LEU, which under the current approach is necessary to power the TVA reactor that produces tritium. NNSA recognizes that its unobligated LEU inventory is finite and declining and has taken actions to extend existing supplies of unobligated LEU in the near term. These actions have effectively bought the agency some time while it initiates an analysis of alternatives process to develop a long-term solution.

However, the scope of the mission need statement underpinning the analysis of alternatives is unclear because it can be interpreted to fulfill more than one mission, which is inconsistent with DOE directives that such a statement should be a clear and concise description of the gap between current capabilities and the mission need. The mission need statement is also inconsistent with the directives' requirement that the mission need should be independent of a particular solution and not be defined by a technological solution or physical end-item. In addition, the mission need statement indicates a preference for using enriched uranium to continue the tritium production mission and excludes consideration of certain technology options, such as one that may have the potential to produce tritium without the need for enriched uranium. Without revising the scope of the mission need statement to clarify which mission need it seeks to achieve and adjusting, as appropriate, the range of options being considered in the analysis of alternatives, NNSA may not consider all options that could satisfy its ultimate mission need.

Further, the preliminary cost estimates developed by NNSA for the large centrifuge and small centrifuge technology options were limited in scope—sized for a capacity to enrich uranium only for tritium production—and do not reflect the full costs of building a uranium enrichment facility that could eventually meet a range of enriched uranium mission needs. By ensuring that the scope of the cost estimates address additional costs that align with other mission needs that the enrichment capability may be intended to fulfill, NNSA can select a more effective option. In addition, we found that the cost estimates produced for this more limited scope do not fully meet the best practice characteristics of reliable cost estimates. By developing reliable cost estimates consistent with best practices, NNSA will ensure that it has quality information to make an informed decision about which option to select.

Recommendations for Executive Action

We are making the following two recommendations to NNSA:

The NNSA Administrator should revise the scope of the mission need statement to clarify which mission need it seeks to achieve and, as appropriate, adjust the range of options considered in the analysis of alternatives process. (Recommendation 1)

The NNSA Administrator should—following clarification of the scope of the mission need statement—ensure that the agency's cost estimates for whichever options it considers going forward are aligned with the scope of the mission need that the enrichment capability is intended to fulfill and that they are developed consistent with best practices. (Recommendation 2)

Agency Comments and Our Evaluation

We provided drafts of this report to NNSA, State, DOD, and TVA for review and comment. In written comments, which are summarized below and reproduced in appendix V, NNSA neither agreed nor disagreed with our recommendations. However, NNSA stated that it will take future actions consistent with our recommendations. NNSA also provided technical comments, which we considered and incorporated as appropriate. The State Department provided technical comments, which we incorporated as appropriate. The Department of Defense stated that it did not have any written or technical comments and TVA did not provide written or technical comments. We also provided a technical statement of facts to the following entities: Centrus, ConverDyn, GMIS, and URENCO. We received technical comments and incorporated them, as appropriate.

In its written comments, NNSA clarified that its mission need statement is written to support a range of requirements, the most urgent of which is LEU for tritium production. Further, NNSA stated that it will evaluate a broader range of options to meet its mission need during the analysis of alternatives process, which has begun and which NNSA has targeted for completion by December 2019. Because the analysis and selection of alternatives in the CD-1 phase builds off of the mission need statement, we believe NNSA's clarification of its mission need statement is positive and will help result in an analysis of alternatives that does not limit potential solutions.

NNSA also stated that it will produce higher fidelity cost estimates leading up to the CD-1 phase, which we agree is consistent with our recommendation. NNSA stated that the preliminary cost estimates it developed do not include the full life cycle cost of building an enrichment facility to meet the range of enriched uranium missions it has now clarified as its mission need, but it stated that such estimates are neither required nor cost beneficial at this early stage. As we noted, best practices—which can be used to evaluate preliminary cost estimates—recommend having complete life cycle cost estimates even at this early stage because they help ensure that all costs are considered to support decision-making and that resources are efficiently allocated to support the project. As NNSA develops its higher fidelity estimates, following cost estimating best practices—such as, by ensuring that the cost estimates for the alternatives being evaluated align with the broad range of uranium mission needs that those alternatives are intended to address, and that full life cycle cost estimates are developed for each option—would better position NNSA to select an option going forward.

We are sending copies of this report to the appropriate congressional committees, Secretary of Energy, Secretary of State, Secretary of Defense, Vice President for Government Relations of TVA, and other interested parties. In addition, this report will be available at no charge on the GAO website at http://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-3841 or at bawdena@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix VI.

Allison B. Bawden
Director, Natural Resources and Environment

Appendix I: Objectives, Scope, and Methodology

The objectives of our review were to assess (1) the actions the National Nuclear Security Administration (NNSA) is taking to extend its existing inventories of enriched uranium to address near-term tritium needs and the costs, schedules, and risks of those actions; (2) the extent to which NNSA's plan to analyze options for supplying enriched uranium in the long term is consistent with Department of Energy (DOE) directives; and (3) NNSA's preliminary cost estimates for long-term uranium enrichment technology options and the extent to which they meet best practices for reliable estimates.

To inform all three objectives, we analyzed NNSA planning documents, such as NNSA's October 2015 *Tritium and Enriched Uranium Management Plan Through 2060* and other documents from NNSA and DOE pertaining to the management of enriched uranium and tritium. We also interviewed officials from NNSA, DOE, the Department of Defense (DOD), the Department of State (State), the Tennessee Valley Authority (TVA) and representatives of companies participating in different stages of the nuclear fuel cycle. We conducted site visits to the Oak Ridge National Laboratory (ORNL), the Y-12 National Security Complex in Oak Ridge, Tennessee, and the American Centrifuge Plant, in Piketon, Ohio, to understand the technology and nonproliferation policy issues that affect the current inventory and future supply of unobligated enriched uranium.

To describe the actions NNSA is taking or plans to take to extend its existing inventories of enriched uranium to address near-term tritium needs and the costs, schedules, and risks of those actions, we reviewed and analyzed agency documents pertaining to NNSA's estimates of the costs, schedules, and risks for the actions. Namely, we analyzed NNSA's October 2015 *Tritium and Enriched Uranium Management Plan Through 2060* and other NNSA strategies and implementation plans, including a 2014 Uranium Inventory Working Group assessment of near-term NNSA actions to extend the supply of unobligated LEU. We interviewed NNSA and TVA officials to validate the cost and schedule information for the action NNSA is taking to extend its LEU inventory. To compare the estimated costs to the actual costs for the actions NNSA is taking or plans to take to extend the unobligated LEU fuel supply for tritium production, we analyzed contracts between TVA and fuel cycle facilities for book storage and associated documentation. We then spoke with representatives from NNSA's downblending contractor, and compared that information to the costs that had been invoiced through July 2017. To identify risks of the options that NNSA has identified, we reviewed NNSA documents and interviewed NNSA officials.

To assess the extent to which NNSA's plan to analyze options for supplying enriched uranium in the long term is consistent with DOE directives, we reviewed DOE and NNSA documents including: documents associated with DOE's critical decision process, such as the uranium enrichment mission need statement, project requirements, and the CD-0 approval memo; DOE memos on the department's uranium management strategy; and an intellectual property transfer contract between DOE and the United States Enrichment Corporation (USEC). We compared these documents to DOE directives, including DOE Order 413.3B *Program and Project Management for the Acquisition of Capital Assets* and 413. 3-4A *Technology Readiness Assessment Guide*, and associated guidance, such as DOE 413.3-17 *Mission Need Statement Guide*.

ORNL and its subcontractor manage the contracts to develop and preserve the large centrifuge technology (AC100), and the contract to develop the small centrifuge technology; therefore, we also reviewed ORNL documents including a uranium enrichment production technology study, project management plans for the large and small centrifuge projects, and large centrifuge experiment test results.

We interviewed DOE officials and ORNL representatives regarding efforts to assess the feasibility of other technology options identified in NNSA's October 2015 plan—large centrifuge, small centrifuge, Atomic Vapor Laser Isotope Separation (AVLIS), Electromagnetic Isotope Separation (EMIS), Separation of Isotopes by Laser Excitation (SILEX), and the Paducah Gaseous Diffusion Plant. We also reviewed documents and interviewed representatives from Centrus and Global Laser Enrichment (GLE)—a joint venture that developed SILEX—regarding the development of the large centrifuge, AVLIS, and SILEX technologies. In addition, we reviewed industry responses to NNSA's request for information regarding proposals for meeting NNSA's future enriched uranium needs. We also interviewed NNSA and DOE officials, and industry representatives, to learn about any recent alternative tritium production technology developments. We conducted a site visit to an isotope production facility in Henderson, Nevada, to observe a NNSA-funded demonstration project with Global Medical Isotope Systems that is currently testing an alternative tritium production technology. To review the feasibility of policy and other options that NNSA is evaluating, we analyzed NNSA planning documents, and interviewed officials from NNSA and State to determine the extent to which the costs, schedules, and risks for these options were known.

To examine NNSA's preliminary cost estimates for long-term uranium enrichment technology options—the large and small centrifuges—and the extent to which they meet best practices for reliable estimates we compared these estimates to GAO's Cost Estimating and Assessment Guide (cost guide), which is a compilation of best practices that federal cost estimating organizations and industry use to develop and maintain reliable cost estimates throughout the life of an acquisition program.[1] According to the cost guide's best practices, four characteristics make up reliable cost estimates—they are comprehensive, well-documented, accurate, and credible. To develop our assessments, we interviewed an NNSA official and a representative of an NNSA contractor who prepared the cost estimates about their methodologies and the findings that were used to support the cost estimates presented in NNSA's mission need statement. We analyzed the cost estimating practices used by NNSA against the four characteristics of reliable cost estimates. We performed a summary analysis because NNSA's cost estimates were at the rough-order-of-magnitude level. After conducting our initial analyses, we shared them with NNSA officials to provide them an opportunity to comment and identify reasons for observed shortfalls in cost estimating best practices. We took their comments and any additional information they provided and incorporated them to finalize our assessment. While rough-order-of-magnitude estimates should never be considered high-quality estimates, rough-order-of-magnitude estimates can be considered reliable by fully or substantially meeting industry best practices. For example, we have found that other rough-order-of-magnitude estimates substantially or fully met various characteristics of a reliable cost estimate, such as cost estimates prepared by the DOD[2] and the U.S. Customs and Border Protection within the Department of Homeland Security.[3] Moreover, DOE's cost guidance states that, "regardless of purpose, classification, or

[1]*GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs (Supersedes GAO-07-1134SP),* GAO-09-3SP (Washington, D.C.: Mar. 2, 2009).

[2]GAO, *Spectrum Management: Federal Relocation Costs and Auction Revenues,* GAO-13-472 (Washington, D.C.: May 22, 2013).

[3]GAO, *Arizona Border Surveillance Technology: More Information on Plans and Costs Is Needed before Proceeding,* GAO-12-22 (Washington, D.C.: Nov. 4, 2011).

technique," the agency's cost estimates should demonstrate quality sufficient for its intended use, be complete, and follow accepted standards such as our cost guide.[4] DOE's cost guidance also describes good cost estimates as including a full life-cycle cost estimate, among other things. These best practices should result in reliable and valid cost estimates that management can use for making informed decisions.

We conducted this performance audit from August 2016 to February 2018 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[4]Department of Energy, *Cost Estimating Guide*, DOE Guide 413.3-21 (Washington, D.C.: May 9, 2011).

Appendix II: Other Options for Obtaining Enriched Uranium without Acquiring a New Uranium Enrichment Capability

The National Nuclear Security Administration (NNSA) has identified other options for obtaining enriched uranium to evaluate in its analysis of alternatives process, but these options pose significant challenges and are likely to be eliminated during this process, according to NNSA and Department of State (State) officials. These options may require changes in policy and could have significant costs, risks, or technical challenges, according to NNSA and State officials. These options include revising domestic policy and international agreements to allow the use of foreign-obligated enriched uranium and technology for producing tritium; obtaining low enriched uranium (LEU) through the Mutual Defense Agreement between the United States and the United Kingdom; downblending highly enriched uranium (HEU) from the defense programs inventory; and reprocessing spent U.S. nuclear fuel. NNSA officials stated that they do not plan to pursue these options at this time.

Revising Domestic Policy and International Agreements to Allow the Use of Foreign-Obligated Uranium and Technology for Producing Tritium

Over the years, questions have been raised as to whether using foreign-obligated material and technology to produce LEU, which produces tritium that can be harvested for weapons, when irradiated in a power reactor, constitutes a peaceful use. However, according to DOE, it has been the agency's long-standing practice to use only unobligated material for tritium production. NNSA's mission need statement includes the option to revise domestic policy and seek to renegotiate international agreements to allow foreign-obligated LEU—that is, LEU either sourced from foreign countries or produced using non-U.S. equipment or technology—for tritium production for nuclear weapons.[1]

Specifically, NNSA discussed three variations of the option of using foreign-obligated LEU for tritium production for use in nuclear weapons:

- Using obligated LEU from URENCO—a European enrichment consortium operating an enrichment plant in New Mexico. The LEU produced by URENCO is enriched using foreign technology and is subject to a peaceful use provision in an international agreement between the United States and Germany, the Netherlands, and the United Kingdom.[2]
- Loading TVA reactor cores with a mix of unobligated and obligated LEU fuel proportional to the extent that the reactor core is used for tritium production for commercial electricity production.
- Renegotiating international agreements to allow the use of foreign technologies to produce LEU for tritium production.

According to NNSA and State Department officials, longstanding U.S. policy will likely preclude the use of these options. A 1998 interagency review—led by DOE—considered the nonproliferation issues associated with establishing a new means for tritium production.[3] The 1998 review concluded that DOE should exclusively use LEU that is unobligated by

[1]We reviewed options for using enrichment technology governed by three international agreements in 2014 and noted that only one of them explicitly addressed the permissibility of tritium production. See GAO, *Department of Energy: Interagency Review Needed to Update U.S. Position on Enriched Uranium That Can Be Used for Tritium Production,* GAO-15-123 (Washington, D.C.: Oct. 14, 2014)

[2]*Agreement between the Three Governments of the United Kingdom of Great Britain and Northern Ireland, the Federal Republic of Germany and the Kingdom of the Netherlands and the Government of the United States of America regarding the Establishment, Construction and Operation of a Uranium Enrichment Installation in the United States* (July 24, 1992).

[3]Congress directed the review in the conference report accompanying the National Defense Authorization Act for Fiscal Year 1998. Participants in the review included the Departments of Defense, Energy, and State; the Arms Control and Disarmament Agency; the Nuclear Regulatory Commission; the National Security Council; the White House Office of Science and Technology Policy; and the Office of the Vice President. See *Interagency Review of the Nonproliferation Implications of Alternative Tritium Production Technologies under Consideration by the Department of Energy*, Report to the Congress (July 1998).

peaceful-use restrictions to preserve the "military/civilian dichotomy."[4] Since that time, NNSA has adhered to this policy and used only unobligated LEU for tritium production, as we reported in 2015.[5] Various U.S. interagency policy committees—which provide national security policy analysis within the National Security Council—met several times between 2014 and 2016 to reexamine the policy and consider whether to allow obligated LEU to be used for tritium production for nuclear weapons. However, the committees concluded that this is not permissible either by the United States or partner countries under applicable international agreements. Revising the policy and agreements would have significant repercussions on U.S. nonproliferation policy as well as on international agreements, according to NNSA and State officials.[6] In addition, according to the mission need statement, U.S. partners have repeatedly requested assurances that materials supplied to the United States not be used for tritium production.

In addition, NNSA and State officials stated that using only unobligated LEU for national security purposes supports U.S. nonproliferation policy goals by, for example, avoiding setting a precedent for other countries that may seek to use U.S. obligated LEU for military purposes. State officials stated that even using a mix of unobligated and obligated LEU fuel would still essentially be asking a foreign partner for the use of its material for tritium production for nuclear weapons. Revising policy to allow for the use of obligated LEU in tritium production could "blur the line" between using LEU for peaceful energy purposes and national security purposes, according to these officials.

[4]The review evaluated the appropriateness of using a TVA commercial reactor whose primary mission was civilian electric power generation for the secondary purpose of producing tritium for defense use. The review noted that potential concerns about divergence from the military/civilian dichotomy regarding the use of a commercial reactor for tritium production could be mitigated in part by the fact that the reactor was wholly owned by the federal government, rather than by a private entity and, therefore, would be in effect extending the past practice of using government-owned facilities simultaneously for civil and military purposes rather than setting a precedent.

[5]See GAO, *Department of Energy: Interagency Review Needed to Update U.S. Position on Enriched Uranium That Can Be Used for Tritium Production,* GAO-15-123 (Washington, D.C.: Oct. 14, 2014).

[6]We previously reported that there could be alternative interpretations of the peaceful-use provisions in certain international agreements with regard to the production of tritium and recommended that DOE reexamine its position through an interagency review process, which it has now done, resulting in a reaffirmation of the position. See GAO-15-123.

Mutual Defense Agreement

NNSA also considered obtaining LEU from the United Kingdom under our mutual defense agreement with that country.[7] The agreement provides for the transfer of special nuclear material between the two countries. In 2014, the Senate Armed Services Committee directed DOE to evaluate whether it would be possible to obtain LEU for the purposes of tritium production from the United Kingdom under the mutual defense agreement.[8] According to State officials, the mutual defense agreement does not preclude the United States from obtaining LEU directly from the United Kingdom for the purposes of tritium production. However, this option is not likely to be pursued by the federal government, according to NNSA officials. Aside from the mutual defense agreement, State officials said that they are not aware of any other such agreements that would potentially allow the United States to obtain tritium from another country.

Downblending of HEU from the Strategic Reserve

NNSA's October 2015 plan identifies a Strategic Reserve of HEU maintained by NNSA as a potential source of HEU for downblending to obtain unobligated LEU for use in tritium production. The Strategic Reserve consists of HEU metal and HEU in nuclear weapon components that are held as a backup for weapons in the U.S. nuclear stockpile.[9] According to the October 2015 plan, this option could provide unobligated LEU for tritium production for many years. However, the October 2015 plan states that changing the quantity of HEU held in the Strategic Reserve inventory would require presidential approval.

NNSA officials indicated that the agency is assessing the costs and risks of this option. According to these officials, pursuing this option would involve significant costs and risks associated with lowering the material in the Strategic Reserve, as well as accelerating the dismantlement of nuclear weapons and the disassembly of their components. While this

[7]*Agreement between the Government of the United Kingdom of Great Britain and Northern Ireland and the Government of the United States of America for Co-operation on the Uses of Atomic Energy for Mutual Defense Purposes* (July 3, 1958).

[8]S. Rep. No. 113-176, at 290-91 (2014) (accompanying the Carl Levin National Defense Authorization Act for Fiscal Year 2015).

[9]The U.S. nuclear weapons stockpile includes air-delivered bombs, ballistic missile warheads, and cruise missile warheads.

option is currently being assessed for costs and risks, NNSA officials noted that there is currently “no plan” to access material from the Strategic Reserve.

Finally, the United States’ inventory of HEU is finite; the United States has not had a domestic capability to produce HEU since 1992 and instead meets national security needs using an inventory of HEU that was enriched prior to 1992. Using this inventory for HEU downblending would consume HEU that could be used to meet other national security missions, such as providing HEU fuel for the U.S. Navy’s propulsion reactors. Consequently, this option could accelerate the date when a new enrichment capability for HEU production would be needed.

Reprocessing Spent U.S. Nuclear Fuel

In its October 2015 plan, NNSA identified an option of reprocessing spent U.S. nuclear fuel to obtain unobligated HEU that could be downblended to LEU and used for tritium production. However, this option was not ultimately included in NNSA’s October 2016 mission need statement.[10] This material is spent reactor fuel from the U.S. Navy and other sources, and represents a potentially significant source of unobligated LEU that could be used for tritium production. DOE maintains a large inventory of such fuel, which includes both aluminum-clad and non-aluminum clad fuel, such as zirconium-clad fuel.[11] Most of the aluminum-clad fuel is stored at the Savannah River Site, in South Carolina, while most of the zirconium-clad fuel is stored at the Idaho National Laboratory.

Options for recovering HEU from either type of spent fuel are limited. The United States can only process and recover HEU from aluminum-clad spent nuclear fuel using the Savannah River Site’s H-Canyon facility, which is the only hardened nuclear chemical separations plant still in operation in the United States.[12] There is a small amount of aluminum-

[10]Reprocessing is the chemical separation of usable uranium or plutonium from burnt or spent nuclear reactor fuel.

[11]Cladding is the outer layer of metal over the fissile material of a nuclear fuel element. The cladding on DOE’s spent nuclear fuel is aluminum or non-aluminum (zirconium or stainless steel).

[12]The name of the facility refers to the appearance of the building. The interior of the building resembles a canyon because the processing areas resemble a gorge in a deep valley between steeply vertical cliffs.

clad fuel at the Idaho National Laboratory that would need to be shipped to the Savannah River Site. However, according to NNSA officials, it would be expensive to transport the material from the Idaho National Laboratory to the Savannah River Site, and the costs to operate H-Canyon to process the material would be high. Further, receipts of all nuclear material at H-Canyon have been halted by Savannah River Site's management and operations contractor due to the facility's degraded conditions and seismic risks.[13] Even if H-Canyon were to resume operations, NNSA officials stated that processing aluminum-clad spent fuel would yield relatively small quantities of LEU usable for tritium production, as a considerable portion of the spent fuel is encumbered under a 1994 Presidential declaration.[14] Therefore, NNSA officials reported that this is considered a long-term option due to the high costs and risks involved.

DOE's Office of Nuclear Energy is researching a process that could recover HEU from the zirconium-clad spent naval reactor fuel. In May 2017, Idaho National Laboratory completed a study examining the feasibility of processing a portion of its zirconium-clad spent fuel inventory through a new process called "ZIRCEX." The report concluded that ZIRCEX showed promise; however, it also noted that pilot-scale testing was needed to prove that it can be used effectively at production scale. According to DOE officials, a pilot-scale demonstration is planned using ZIRCEX, with limited testing planned in fiscal year 2018. DOE officials told us the costs and schedules to implement a full-scale production plant using ZIRCEX to recover HEU from zirconium clad spent fuel are not

[13]A June 30, 2017 memo from the Defense Nuclear Facilities Safety Board states that H-Canyon and HB Line – which sits atop Savannah River Site's H-Canyon and helps feed the material through—are not currently taking materials for processing citing potential safety issues should an earthquake occur. It is unclear whether this is a short-or long-term suspension of work. According to NNSA officials, federal staff at Savannah River Site confirmed that H-Canyon is on a six-month outage to reconfigure a dissolver for processing the fuel for the High Flux Isotope Reactor at Oak Ridge National Laboratory and anticipates resuming fuel processing in January 2018. HB Line is offline for another 18-22 months until—following a safety analysis—they complete the modeling of potential degradation of a ventilation duct.

[14]Quantities of HEU were declared excess to national security needs in 1994 and 2005, which made some of this excess HEU available for downblending. According to NNSA documents, the 1994 declaration by the President pledged that 174 metric tons of HEU would never again be used for any military purpose, including naval propulsion and tritium production. In 2005, the Secretary of Energy declared 200 tons of HEU excess to the weapons program. According to NNSA documents, the 2005 declaration specifically allowed for use of this material for naval propulsion and tritium production.

known. Furthermore, additional processing and downblending would be needed to produce unobligated LEU. DOE considers recovering unobligated HEU for tritium production for use in nuclear weapons through the ZIRCEX process a long-term possibility that could be re-evaluated as the technology matures.

Appendix III: Other Uranium Enrichment Technologies

In addition to the large and small centrifuges, four other enrichment options were presented in the National Nuclear Security Administration's (NNSA) October 2015 plan and its October 2016 mission need statement. However, these options are unlikely to be pursued, according to NNSA documents. Some of these options have produced enriched uranium in the past, but extraordinary technical or financial barriers, past research failures, or peaceful use restrictions will likely preclude further consideration by NNSA, according to agency documents. These options include:

- **Restart of the Paducah Gaseous Diffusion Plant (GDP).** Gaseous diffusion was the first uranium enrichment technology used for both national security and commercial enriched uranium needs in the United States, and involves passing uranium hexafluoride in a gaseous form through a series of filters that is then cooled into a solid. The Paducah GDP produced low enriched uranium (LEU) from the mid-1950s until 2013.[1] It was originally operated by the Department of Energy (DOE), but leased to the United States Enrichment Corporation (USEC) beginning in 1993. Gaseous diffusion facilities used very large amounts of electricity, making them costly to operate. According to DOE, by May 2012, it became clear that USEC was no longer in a financial position to continue enrichment activities at the Paducah GDP, and—through a series of transactions—DOE transferred enough material to keep it operating long enough to produce an additional 15-year supply of LEU for future tritium production.[2] In May 2013, USEC ceased enrichment at the Paducah GDP citing the high costs of maintaining and operating an aging

[1]DOE originally operated three gaseous diffusion facilities in Paducah, Kentucky; Piketon, Ohio; and Oak Ridge, Tennessee. The Oak Ridge facility closed in 1985, and the Piketon facility closed in 2001.

[2]As we reported in May 2014, in 2012 DOE transferred a significant quantity of depleted uranium tails to a third party, which paid USEC to enrich the tails. This transaction effectively kept the Paducah GDP in operation from 2012 through May 2013, when USEC completed the tails enrichment. DOE conducted this transaction in part to ensure the availability of a 15-year supply of unobligated low-enriched uranium for future tritium production. See GAO-14-291.

plant.[3] In October 2014, the Paducah GDP was returned to DOE, and DOE is currently deactivating the plant in preparation for decontamination and decommissioning, while it continues to complete environmental cleanup that began in the late 1980s.

In April 2015, when NNSA produced a technical evaluation of uranium enrichment technology options, restarting the Paducah GDP was still a hypothetical possibility. At that time, NNSA estimated that the technology readiness level (TRL) for this option rated 7-8 on the TRL scale. Restarting the Paducah GDP was advantageous, according to NNSA, because of the facility's high production rate. For example, according to DOE officials, if it had been operated for a relatively brief period of time after May 2013, a significant stockpile of unobligated LEU could have been produced to support tritium production for a number of years. Since 2015, the plant and equipment have significantly deteriorated, and restart of the Paducah GDP is no longer a feasible option, according to NNSA documents and Oak Ridge National Laboratory (ORNL) representatives. Due to degradation of the equipment, the expected rate of equipment failure, a lack of replacement parts, the dispersion of trained and qualified personnel, and ongoing decontamination and demolition activities, a major effort would be required to reconstitute the plant, according to NNSA's 2015 technical evaluation and the 2015 plan. NNSA's 2015 evaluation estimated that it would cost $425 million to $797 million to restart the plant, and between $554 million to $1 billion annually to operate it. In addition, even if the Paducah GDP were successfully restarted without major failures, the plant could likely operate at full capacity for only 1 to 3 years before incurring additional significant costs for repairs, and obtaining replacement parts for critical process equipment would be difficult. According to NNSA's April 2015 evaluation, operating the Paducah GDP beyond 1 to 3 years would require major investments in the plant's facilities and infrastructure.

- **Electromagnetic Isotope Separation (EMIS).** Electromagnetic isotope separation was used in the United States to enrich uranium for the Manhattan Project, but was abandoned in favor of the then-less-costly gaseous diffusion technology. Electromagnetic separation used magnetic and electronic forces to manipulate and separate charged isotopes. An updated EMIS machine has been developed by ORNL that was successful at the laboratory scale, and which had a

[3]The cost to operate the plant in fiscal years 2009 through 2010 was approximately $1.05 billion per year, according to an NNSA document.

TRL of 7, according to NNSA documents and ORNL representatives.[4] However, when scaled to production levels, NNSA estimated that an enrichment facility using EMIS would require over 60,000 machines and cost approximately $150 billion to construct. Due to the exorbitant estimated costs, this option is unlikely to be pursued by NNSA, according to agency documents.

- **Atomic Vapor Laser Isotope Separation (AVLIS).** Lawrence Livermore National Laboratory and later, USEC, developed the AVLIS technology from 1973 through 1999. This technology relies on the phenomenon that different isotopes of uranium absorb laser light at different wavelengths. Because lasers can be finely tuned, the ability to separate the uranium-235 isotope from the uranium-238 isotope is potentially much greater than with gaseous diffusion or the gas centrifuge process. However, despite the federal government spending $1.7 billion on the technology, and USEC investing an additional $100 million, it was not successful at the pilot scale stage and USEC ended research and funding in 1999. According to NNSA's October 2015 plan, AVLIS' TRL was estimated to be 5-6.[5] If development were restarted, AVLIS could reach a TRL of 9— ready to deploy—in 5 to 15 years, according to NNSA's October 2015 plan. However, this would likely be too late to meet NNSA's 2038 to 2041 need date for additional unobligated LEU, and there is no estimate for the cost of such a plant, according to agency documents. According to NNSA's 2015 plan, there is no current effort to develop the AVLIS technology.
- **Separation of Isotopes by Laser Excitation (SILEX).** Global Laser Enrichment (GLE)—a joint venture between General Electric, Hitachi, and Cameco—is developing this uranium enrichment technology that also uses lasers to separate isotopes.[6] The technology is proprietary and was developed, in part, by an Australian company. In November 2016, DOE reached an agreement to sell its depleted uranium tails to GLE for re-enrichment to natural uranium. According to a senior SILEX official, GLE intends to build an enrichment plant by 2025

[4]TRL 7 is when a full scale, similar (prototypical) system has been demonstrated in a relevant environment.

[5]TRL 5-6 is between demonstration of a laboratory scale system and demonstration of a pilot scale system.

[6]General Electric and Hitachi announced in April 2016 that they intend to exit SILEX due to changing priorities and changing fuel markets. The corporate restructuring of SILEX is ongoing.

adjacent to the site of the former Paducah GDP to re-enrich these tails. However, we previously found that the SILEX agreement between the United States and Australia likely prohibits using LEU produced using GLE's process for the subsequent production of tritium, and the executive branch has long interpreted it as such.[7]

[7]GAO-15-123; *Agreement for Cooperation Between Australia and the United States of America Concerning Technology for the Separation of Isotopes of Uranium by Laser Excitation,* Oct. 28, 1999.

Appendix IV: Centrus' Centrifuge Development

The AC100 centrifuge (large centrifuge) design was developed by USEC Inc. (now Centrus),[1] based off Department of Energy (DOE) centrifuge research that was terminated in the 1980s.[2] Standing about 40 feet tall, its size means that it can produce more separative work units (SWU) per centrifuge than other centrifuge designs—making it the most advanced centrifuge design in the world, according to Centrus.[3] In contrast to European and Japanese centrifuge designs, which are relatively small (2 to 4 meters long) and have separative work capacities in the range of 5 SWU per year to 100 SWU per year, the AC100 demonstrated a SWU production rate greater than 340 per year.

When it leased a DOE site at Piketon, Ohio, for its American Centrifuge demonstration plant starting in 2004, USEC originally intended to build a 3.8 million SWU commercial uranium enrichment plant at that site with enough land nearby to expand the facility to meet total U.S. low enriched uranium (LEU) demand, including enough to meet national security needs.[4] The planned facility would have included over 14,400 centrifuges in a facility covering over 2 million square feet. In 2010, and again in

[1]In 1992, the United States Enrichment Corporation was established as a government corporation to operate DOE's enrichment facilities, among other things. In 1998, the United States Enrichment Corporation was privatized under the USEC Privatization Act and became a subsidiary of the newly created USEC Inc. In September 2014, following Chapter 11 bankruptcy proceedings, USEC Inc. changed its name to Centrus Energy Corp. For the purposes of this report, we will refer to the company as United States Enrichment Corporation when discussing events prior to privatization, USEC Inc. (USEC) when discussing events between privatization and September 2014, and we will refer to the company as Centrus when discussing events after September 2014.

[2]After spending more than $2.5 billion on its development, DOE ended research into gas centrifuge technology in 1985 due to budget constraints. In 2002, DOE and USEC signed an agreement that committed both parties to further develop centrifuge technology for uranium enrichment and DOE licensed the technology to USEC. According to USEC, the company has cumulatively spent an additional $2.5 billion to update the technology and reestablish the manufacturing infrastructure that was lost when DOE abandoned the technology.

[3]The effort needed to enrich a given amount of natural uranium into LEU or highly enriched uranium is measured in separative work units (SWU).

[4]The demonstration plant is collocated with Portsmouth Gaseous Diffusion Plant in Piketon, Ohio—a former USEC enrichment plant which was shut down in 2001.

2012, DOE and USEC signed cooperative agreements to share the cost of supporting a research, development, and demonstration program for the large centrifuge technology. DOE provided $280 million, or 80 percent of the investment in the program, with the remaining $70 million, or 20 percent, provided by USEC. With this support, USEC began operating a 120-machine commercial demonstration cascade in October 2013.

In the wake of significant adverse uranium market impacts resulting from the Fukushima Daiichi accident in Japan in 2011, and in light of difficulties in securing DOE loan guarantees for deploying a commercial plant, USEC declared bankruptcy in March 2014 and later emerged as Centrus. In April 2014, following the conclusion of the cooperative agreement, the Secretary of Energy stated that DOE's Oak Ridge National Laboratory would place Centrus under contract to operate the demonstration plant and technology with a focus on meeting national security needs. In May 2014, Centrus entered into a contract with UT-Battelle—DOE's contractor for Oak Ridge National Laboratory—to run a program to preserve and further advance the technology readiness of the AC100 technology. Also, since 2002, Centrus has maintained a lease on a smaller test research facility, K-1600, at Oak Ridge, Tennessee, from DOE. According to a DOE document, centrifuges can be assembled and balanced at K-1600, and the test facility allows verification of centrifuge operations beyond what was possible at the demonstration plant. The K-1600 facility is located near Centrus' manufacturing hub, the American Centrifuge Technology & Manufacturing Center, also in Oak Ridge, Tennessee.

Because the May 2014 contract was set to expire in September 2015, Centrus and UT-Battelle began negotiating a new contract to support operations at the demonstration plant, the Technology and Manufacturing Center, and K-1600 in early 2015. UT-Battelle and Centrus agreed to an extension of research operations at K-1600 and the Technology and Manufacturing Center until September 2016 for $35 million annually. In addition, the Centrus lease of K-1600 was renewed until the end of calendar year 2017. However, the parties were unable to agree on further funding for the demonstration plant. On September 11, 2015, DOE announced that it would not fund the demonstration plant in Piketon, Ohio, after September 30 of that year. Centrus—unable to operate the demonstration plant without further government support—announced its intention to demobilize the plant in February 2016. Decontamination and decommissioning of the demonstration plant began in April 2016. As part of this work, Centrus is removing all of the equipment—including the centrifuges—from the demonstration plant, and will finish disposing of the machines at a secure government facility in October 2017, according to

Centrus officials. However, according to DOE officials, DOE has preserved a number of the centrifuges and associated components at the Technology & Manufacturing Center. Centrus documents anticipate that the decontamination and decommissioning work will be substantially complete by the end of 2017. According to NNSA officials, Centrus has given verbal notice to DOE that it intends to terminate its American Centrifuge demonstration plant site lease in 2019.

An August 2015 DOE memo states that technical issues with the existing centrifuges, peaceful-use restrictions on key components and DOE's acquisition timeline meant that there was limited value in continuing to support the demonstration cascade after 2015. Specifically, during operation of the demonstration cascade, two technical issues were identified that made the existing centrifuges undesirable for future use. Rehabilitation of the centrifuges would have been cost prohibitive, according to NNSA officials. In addition, key components of the existing machines were constructed using foreign-sourced materials, which were subject to peaceful-use restrictions. According to an August 2015 DOE memo, the second cooperative agreement with Centrus did not require that Centrus use unobligated materials, and Centrus initially assumed it would use those machines in a larger commercial plant and not for national security. Centrus representatives and DOE officials told us that the company had since identified U.S. suppliers or workarounds for these components. However, to be used in a national security facility, these components would need to be remanufactured using those suppliers, since not all components in the demonstration cascade were unobligated. Further, under NNSA's timeline for a domestic uranium enrichment capability, it could take until 2027 to begin construction of a uranium enrichment plant. Thus, according to an August 2015 memo, DOE concluded that it would not be economical to keep the demonstration cascade operational, and that, after the passage of so much time, parts of the centrifuges and the balance of the plant would also need to be replaced during construction.

Appendix V: Comments from the Department of Energy / National Nuclear Security Administration

Department of Energy
Under Secretary for Nuclear Security
Administrator, National Nuclear Security Administration
Washington, DC 20585

National Nuclear Security Administration

January 26, 2018

Ms. Allison B. Bawden
Director, Natural Resources
and Environment
U.S. Government Accountability Office
Washington, DC 20548

Dear Ms. Bawden:

Thank you for the opportunity to review the Government Accountability Office (GAO) draft report *Nuclear Weapons: NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs and Improve Technology Cost Estimates* (GAO-18-126). The National Nuclear Security Administration (NNSA) appreciates GAO's recognition of actions taken and planned to extend the existing supplies of unobligated low-enriched uranium (LEU).

As the report notes, the domestic uranium mission need statement is written to support a range of requirements, the most urgent of which is LEU for tritium production. Considering a range of mission activities is an approach that supports integrated planning and avoids expensive duplication of effort. The need statement was written to achieve Critical Decision (CD)-0, *Approve Mission Need*, and is not intended to provide a comprehensive list of alternatives. The options presented do not indicate preference nor does the absence of other options necessitate revision to the need statement. Full exploration of potential options will occur during the Analysis of Alternatives (AoA), which occurs between CD-0 and CD-1, *Approve Alternative Selection and Cost Range,* per Department of Energy Order 413.3B, *Program and Project Management for Acquisition of Capital Assets.*

NNSA has initiated the AoA which is targeted for completion by December 2019 and will evaluate a broader range of alternatives than were identified in the mission need statement. The GAO report correctly notes several uncertainties that may affect the final scope of activities. The AoA will further evaluate the universe of DOE needs for enriched uranium, while considering uncertainties and prioritization that will drive schedules.

Finally, the report correctly notes that the preliminary cost estimate does not include the full life-cycle cost of building a uranium enrichment facility that could meet the range of enriched uranium needs. The rough order of magnitude estimates are prepared for the purpose of determining CD authority under DOE Order 413.3B, and it is not required or cost beneficial to include the life-cycle cost of a potential facility at this early stage. NNSA will produce higher fidelity estimates on the final alternatives as it continues through the process leading to CD-1, including appropriate estimates for a facility solution, if selected. DOE's Office of Program Management Oversight and Analysis conducted an Independent Cost Review of the preliminary estimates and deemed them appropriate for the intended purpose.

NNSA is confident that the mission need statement and AoA, once completed, will address GAO's underlying concerns supporting the recommendations in the report. Subject matter experts have provided technical comments under separate cover for your consideration to address these areas, and enhance the clarity and factual accuracy of the report. If you have any questions regarding this response, please contact Dean Childs, Director, Audits and Internal Affairs, 301-903-1341.

Sincerely,

Steven C. Erhart (Acting)

Appendix VI: GAO Contact and Staff Acknowledgments

GAO Contact

Allison B. Bawden, (202) 512-3841 or bawdena@gao.gov

Staff Acknowledgments

In addition to the individual named above, Shelby S. Oakley, Director; William Hoehn, Assistant Director; Eric Bachhuber, Analyst in Charge; Julia Coulter; and Katrina Pekar-Carpenter made key contributions to this report. Also contributing to this report were Antoinette C. Capaccio, Jeff Cherwonik, Jennifer Echard, Robert S. Fletcher, Ellen Fried, Cindy Gilbert, Amanda K. Kolling, Jason Lee, Jennifer Leotta, Dan C. Royer, Anne Stevens, and Kiki Theodoropoulos.

Appendix VII: Accessible Data

Agency Comment Letter

Text of Appendix V: Comments from the Department of Energy / National Nuclear Security Administration

Page 1

January 26, 2018

Ms. Allison B. Bawden Director, Natural Resources and Environment

U.S. Govenunent Accountability Office Washington, DC 20548

Dear Ms. Bawden:

Thank you for the opportunity to review the Government Accountability Office (GAO) draft report Nuclear Weapons: NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs and Improve Technology Cost Estimates (GAO-18-126). The National Nuclear Security Administration (NNSA) appreciates GAO's recognition of actions taken and planned to extend the existing supplies of unobligated low-enriched uranium (LEU).

As the report notes, the domestic uranium mission need statement is written to support a range of requirements, the most urgent of which is LEU for tritium production. Considering a range of mission activities is an approach that supports integrated planning and avoids expensive duplication of effort. The need statement was written to achieve Critical Decision (CD)-0, Approve Mission Need, and is not intended to provide a comprehensive list of alternatives. The options presented do not indicate preference nor does the absence of other options necessitate revision to the need statement. Full exploration of potential options will occur during the Analysis of Alternatives (AoA), which occurs between CD-0 and CD-1, Approve Alternative Selection and Cost Range, per Department of Energy Order 413.3B, Program and Project Management for Acquisition of Capital Assets.

NNSA has initiated the AoA which is targeted for completion by December 2019 and will evaluate a broader range of alternatives than were identified in the mission need statement.

The GAO repo1i correctly notes several uncertainties that may affect the final scope of activities. The AoA will further evaluate the universe of DOE needs for enriched uranium, while considering uncertainties and prioritization that will drive schedules.

Finally, the report correctly notes that the preliminary cost estimate does not include the full life- cycle cost of building a uranium enrichment facility that could meet the range of enriched uranium needs. The rough order of magnitude estimates are prepared for the purpose of determining CD authority under DOE Order 413.3B, and it is not required or cost beneficial to include the life-cycle cost of a potential facility at this early stage. NNSA will produce higher fidelity estimates on the final alternatives as it continues through the process leading to CD-1, including appropriate estimates for a facility solution, if selected. DOE' s Office of Program Management Oversight and Analysis conducted an Independent Cost Review of the preliminary estimates and deemed them appropriate for the intended purpose.

Page 2

NNSA is confident that the mission need statement and AoA, once completed, will address GAO's underlying concerns supporting the recommendations in the report. Subject matter expe1ts have provided technical comments under separate cover for your consideration to address these areas, and enhance the clarity and factual accuracy of the report. If you have any questions regarding this response, please contact Dean Childs, Director, Audits and Internal Affairs,

301-903-1341.

Sincerely,

Steven Earhart (Acting)

GAO’s Mission

The Government Accountability Office, the audit, evaluation, and investigative arm of Congress, exists to support Congress in meeting its constitutional responsibilities and to help improve the performance and accountability of the federal government for the American people. GAO examines the use of public funds; evaluates federal programs and policies; and provides analyses, recommendations, and other assistance to help Congress make informed oversight, policy, and funding decisions. GAO’s commitment to good government is reflected in its core values of accountability, integrity, and reliability.

Obtaining Copies of GAO Reports and Testimony

The fastest and easiest way to obtain copies of GAO documents at no cost is through GAO’s website (https://www.gao.gov). Each weekday afternoon, GAO posts on its website newly released reports, testimony, and correspondence. To have GAO e-mail you a list of newly posted products, go to https://www.gao.gov and select “E-mail Updates.”

Order by Phone

The price of each GAO publication reflects GAO’s actual cost of production and distribution and depends on the number of pages in the publication and whether the publication is printed in color or black and white. Pricing and ordering information is posted on GAO’s website, https://www.gao.gov/ordering.htm.

Place orders by calling (202) 512-6000, toll free (866) 801-7077, or TDD (202) 512-2537.

Orders may be paid for using American Express, Discover Card, MasterCard, Visa, check, or money order. Call for additional information.

Connect with GAO

Connect with GAO on Facebook, Flickr, Twitter, and YouTube.
Subscribe to our RSS Feeds or E-mail Updates. Listen to our Podcasts.
Visit GAO on the web at https://www.gao.gov.

To Report Fraud, Waste, and Abuse in Federal Programs

Contact:

Website: https://www.gao.gov/fraudnet/fraudnet.htm
E-mail: fraudnet@gao.gov
Automated answering system: (800) 424-5454 or (202) 512-7470

Congressional Relations

Orice Williams Brown, Managing Director, WilliamsO@gao.gov, (202) 512-4400, U.S. Government Accountability Office, 441 G Street NW, Room 7125, Washington, DC 20548

Public Affairs

Chuck Young, Managing Director, youngc1@gao.gov, (202) 512-4800
U.S. Government Accountability Office, 441 G Street NW, Room 7149
Washington, DC 20548

Strategic Planning and External Liaison

James-Christian Blockwood, Managing Director, spel@gao.gov, (202) 512-4707
U.S. Government Accountability Office, 441 G Street NW, Room 7814, Washington, DC 20548