# Declaring more U.S. weapon-grade uranium excess could delay by two decades the need to build a new national enrichment plant

Frank von Hippel, Program on Science and Global Security, Princeton Univesity, 5 April 2018

**Abstract.** The U.S. Department of Energy has launched an initiative to bring a small-capacity new national enrichment plant online by 2038 at an estimated cost of $3.1-11.3 billion. The plant's initial mission would be to produce low-enriched uranium (LEU) to fuel two Tennessee Valley Authority power reactors that produce tritium for U.S. warheads as a byproduct. DOE still has more than 200 tons of 93.5% enriched weapon-grade uanium (WgU) in and available for weapons, however. Based on public information, U.S. warheads each contain an average of about 25 kilograms of WgU. Two hundred tons is therefore twice the amount required to support the current active stockpile of about 3,800 U.S. warheads. If 40 tons of this WgU were declared excess and blended down to LEU by 2035-2055, that would be sufficient to fuel U.S. tritium production until about 2060.

## The U.S. need for national enrichment capacity

In March 2017, the U.S. Department of Energy (DOE) issued a request for information that outlined options for providing a new national uranium enrichment capability and in November 2017 held a meeting with industry to discuss these options.[1]

The U.S. government uses enriched uranium for three purposes:

1. Low-enriched uranium (LEU, about 50 tons annually, containing 4.5% chain-reacting U-235) to fuel two Tennessee Valley Authority (TVA) power reactors that produce tritium for U.S. nuclear weapons as a byproduct;[2]
2. High-assay LEU (~1.5 tons/yr, 19.75% enriched) to supply U.S. and foreign research and test reactors;[3] and
3. Weapon-grade uranium (~2.5 tons/yr) to fuel the Navy's nuclear-propulsion reactors.[4]

The basis for these requirements and projections of the years when available supplies will run out are provided in DOE's 2015 *Tritium and Enriched Uranium Management Plan Through 2060*. They could be satisfied by an enrichment capacity of about a million separative work units (SWU) per year.

As the 2015 DOE report explains, the last U.S.-government-owned enrichment plant, a 11.4-million SWU per year gaseous-diffusion plant in Paducah, Kentucky that had been leased to a private company to produce LEU for the commercial market, was shut down in 2013 because it could not compete with the newer, more energy-efficient gas-centrifuge plants that have been built by other countries, including a plant built in New Mexico by the British-Dutch-German consortium, URENCO.

The requirement for which U.S. stocks of enriched uranium will first run out is LEU fuel for the tritium-production reactors. Tritium decays with a half-life of 12.3 years. Unlike the plutonium and HEU in U.S. nuclear weapons, it must therefore be replenished on a regular basis. The DOE report argues that the U.S. cannot fuel its tritium-production reactors with LEU enriched in foreign-owned plants since the tritium is for nuclear weapons and the LEU produced by foreign-owned plants is restricted to peaceful use.

DOE's National Nuclear Security Administration (NNSA) therefore has proposed an enrichment plant sized initially to provide LEU for two TVA tritium-production reactors with a capacity of 0.4 million SWU per year for an estimated cost of $3.1-11 billion.[5] This is a substantial projected cost – especially from an agency that has become known for huge project cost overruns.[6] For comparison, URENCO's commercial enrichment plant in New Mexico, on which construction began in 2006, had a capital investment of about $4 billion at the beginning of 2015 when the plant reached a capacity of 3.7 million SWU, nine times the initial capacity proposed by DOE.[7]

The argument that the U.S. cannot fuel its tritium-production reactors with LEU produced by foreign-owned plants is not uncontested. Indeed, the management of URENCO would be willing to sell LEU to fuel the U.S. tritium-production reactors because its peaceful-use requirement does not cover tritium production.[8] Article III of the U.S. treaty with the URENCO countries relating to the New Mexico plant states:[9]

> "any special nuclear material produced through the use of such [centrifuge] technology [and] any special nuclear material produced through the use of such special nuclear material, … shall only be used for peaceful, non-explosive purposes."

In Article I, where the treaty defines "special nuclear material", however, it is as "plutonium, uranium-233, and uranium enriched in the isotopes U-233 or U-235." Tritium is not on the list.[10]

In any case, the current U.S. government position is that TVA's tritium-production reactors can be fueled only by "unobligated" uranium, defined as with no peaceful-use obligations, most simply, uranium mined in the U.S. and enriched by a U.S.-owned plant. It is this interpretation that justifies the DOE's current drive to build its own enrichment plant.

The 2015 DOE Report provides a rather thorough discussion of the options for obtaining additional unobligated pre-existing LEU or LEU blended down from excess U.S. HEU to fuel two Tennessee Valley Authority (TVA) power reactors to produce tritium for U.S. nuclear weapons as a byproduct. The tritium is produced by inserting rods containing lithium-6 into the reactor cores. When a lithium-6 nucleus absorbs a neutron, it undergoes the reaction n+lithium-6 → tritium + helium-4.

One option for obtaining more unobligated LEU that was discussed only cursorily in the DOE's report was declaring more U.S. HEU excess to weapons requirements and blending it down to LEU. The amount of weapons HEU that the United States has that is not in actual operational weapons was not revealed, however, in the 2015 DOE report.

The purpose of this paper is to estimate the amount of HEU the United States still has available for weapons and how much of that HEU might be declared excess to be blended down to provide LEU fuel for the tritium-production reactors. It is concluded that the quantity is sufficient to delay the need for the production of additional LEU until at least 2060. If that is correct, DOE's proposal to have a new national enrichment plant on line to produce LEU by 2038 may be premature by at least two decades. This conclusion could be checked by analysts with access to the classified information on how much HEU is in U.S. deployed and reserve nuclear warheads.

**How much HEU does the U.S. have available for weapons?**

The best starting point for an unclassified estimate of the amount of HEU that the U.S. has available for weapons is a detailed report of past U.S. production, utilization and stocks of HEU that was prepared during the Clinton Administration as a part of Energy Secretary Hazel O'Leary's "Openness Initiative."[11] This report, *Highly Enriched Uranium, Striking a Balance: A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through Sept. 30, 1996*,[12] had not been finalized when Secretary O'Leary stepped down in January 1997 at the end of President Clinton's first term. After her departure, the process of declassifying the report ground to a halt. It was released in 2001 in response to persistent Freedom of Information requests by Steven Aftergood of the Federation of American Scientists.[13] Updates of the 2001 HEU declaration were released in 2006 and 2016 but the defense bureaucracy had largely reverted its preference for secrecy.[14] The 2006 update gave an update of HEU stocks by site but a great deal of information was suppressed because the nuclear navy, inexplicably, did not want to reveal the average annual rate at which its aircraft carriers and submarines collectively consume HEU. That information is easily estimated from the annual unclassified reports that the Navy provides to the State of Idaho on its shipments of spent naval reactor fuel to the Naval Reactors Facility 50 miles west of Idaho Falls. The 2016 update contained only the total national stock of HEU and the previously published information that about 130 tons of excess HEU had been blended down and that the amount of HEU in spent fuel had increased by about 20 tons.

Table 1 shows the derivation of an estimate of the U.S. HEU in and available for nuclear weapons based on information in *Highly Enriched Uranium, Striking a Balance*, taking into account subsequent actions to reduce this stockpile.

| | **HEU** (tons) | **U-235** (tons) | **Enrichment** (percent) |
|---|---|---|---|
| Inventory as of 30 Sept 1996[15] | 740.7 | 620.3 | 83.7 |
| -of which military[16] | 651.6 | 557.4 | 85.5 |
| -of which naval[17] | ~100 | ~97.4 | 97.4[18] |
| -available for weapons (by subtraction) | 551.6 | 460 | 83.4 |
| -declared surplus in 1994[19] | 102.8 | 59.1 | 57.5 |
| -remaining, available for weapons, 1994 | 448.8 | 400.9 | 89.3 |
| -of which shifted to Navy, 2005[20] | 152 | 142.1[21] | 93.5 |
| –committed to other non-weapon use, 2005[17] | 48 | 26.2-41.8 | 54.6-87.2[22] |
| -remaining military non-naval, 2005 | 248.8 | 232.6-217.0 | 93.5-87.2[23] |
| -proposed blend-down of HEU scrap, 2015[24] | 8.7-32.7 | 8.1-16.4 | 93.5-50.0 |
| **Remaining available for weapons** | **240.1-216.1** | **224.5-200.6** | **93.5-92.8** |

Table 1. Reductions of U.S. HEU available for weapons as a result of the decisions of different administrations.

The first action to reduce the amount of HEU available for weapons subsequent to the 2001 report was by Secretary of Energy Bodman in 2005. Following a Congressionally-driven decision to reduce the number of operational warheads by nearly half, Bodman declared 200 additional tons of HEU excess for U.S. weapons requirements. Of this material, 160 tons were committed to be used for naval-reactor fuel. Bodman stated that this would "have the added benefit of postponing the need high enrichment for at least fifty years."[25] Subsequently, eight of the 160 tons HEU designated by Bodman for a naval reserve were rejected by the Navy as not meeting its specifications. In its 2015 report to Congress, DOE estimated that the remaining 152 tons "will be sufficient to meet [naval reactor] demand through 2060, assuming no changes in projected fleet requirements."[26]

The next to last line in Table 1 shows an estimate of the reduction of the stock of HEU available for weapons due to a small release of scrap from the HEU weapon stocks that was sketched out in the 2015 DOE report as part of a larger effort to increase the stock of "unobligated" and "unencumbered" LEU available for fueling the tritium production reactors beyond Fiscal Year 2027. "Unobligated" has been defined above as not subject to foreign peaceful-use restrictions. "Unencumbered" means that the LEU is not subject to U.S. self-imposed peaceful-use restrictions. Specifically, President Clinton's declaration of 175 tons of HEU excess for weapons purposes in 1994 has been interpreted by DOE as making LEU derived from blend-down of that HEU unavailable to fuel the tritium-production reactors.[27]

One uncertainty in the results shown in Table 1 stems from the assumption that there have been no additions to the weapons stocks from HEU that, in 1996, was located at DOE sites other than the Y-12 HEU site and the Pantex warhead assembly/disassembly site. In 1996, there were a total of 89 tons of HEU at the other sites. All but 14 tons of this material had been declared excess in 1994, however. Of this 14 tons, only 3.8 tons at the site of the shutdown Rocky Flats pit production facility is likely to have been shipped to Y-12 and Pantex.[28] Therefore, the estimate of the amount of U.S. HEU still available for weapons in Table 1 may be low by a few tons.

Including the last reduction in Table 1, the DOE has identified sources of enough LEU to fuel the TVA reactors until approximately 2040. The details are summarized in the Appendix. The 2015 DOE report concluded that, to obtain enough LEU to go further without producing more by new enrichment, it would be necessary to release more HEU from the weapons stockpile for blend-down.

**How much HEU does the U.S. need for weapons?**

The bottom line of Table 1 shows more than 200 tons of weapon-grade uranium in and available for U.S. weapons.

Between 1995 and 2013, the United States bought from Russia LEU blended down from 500 tons of excess Russian weapon-grade uranium. That amount of WgU was described by the U.S. side as "enough bomb-grade material for 20,000 nuclear warheads,"[29] corresponding to 25 kilograms of WgU in the average excess Soviet warhead. That average also is roughly consistent with what one can calculate by dividing U.S. declarations of its own HEU and warhead stockpiles in the 1980s.[30]

Assuming 25 kg of HEU per warhead, the approximately 3,800 warheads in the U.S. nuclear stockpile as of the end of fiscal year 2017[31] would contain about 95 tons of HEU. The most authoritative non-governmental analysis estimates the total number of deployed U.S. warheads as about 1800 with the remaining 2,000 being a reserve.[32] Warheads in the reserve can be used as a “hedge,” to be redeployed if an expansion of U.S. nuclear forces were desired, or used to replace deployed warheads requiring fixing or refurbishment. A one-to-one reserve is very conservative. In addition, there were about 2650 retired warheads awaiting dismantlement.[33]

The United States also has a stockpile of warhead components, including plutonium “pits” and canned subassemblies (CSA). A CSA is the fission-fusion secondary in a thermonuclear weapon that would be ignited by the explosion of the plutonium pit in the fission “primary.” The CSA contains almost all of the HEU in a warhead. If most of the more than 100 tons U.S. HEU not in deployed and reserve warheads is in CSA’s, at an average of 25 kg of HEU each, there would about 4,000 CSAs, including in warheads scheduled for dismantlement, whose HEU has not been declared excess.

Keeping one CSA as a backup for every deployed and reserve warhead seems excessive. Much of the 100 tons of HEU in the CSAs not in operational warheads could be declared excess for weapons. The decision to do so is ordinarily left to the DOD-DOE Nuclear Weapons Council (NWC),[34] however. If history is a guide, the NWC errs on the side of keeping warheads in the stockpile “just in case.”[35] With regard to keeping CSAs, arguments from the nuclear-weapon design laboratories reportedly include preserving high-yield secondaries for possible future use for asteroid defense and keeping four alternative types of CSAs for the future, not-yet-designed warheads of the proposed bomber-carried Long-Range Stand-Off missile that is to replace the current Air-Launched Cruise Missiles.[36]

The 2015 DOE study stated that part of the inventory of national-security HEU is in a Strategic Reserve described as[37]

> “canned subassemblies (CSAs), composite pits, very highly enriched uranium (VHEU), and high purity metal… The material that is not contained within components (CSAs and composite pits) is primarily VHEU (HEU enriched to ~97 percent) and is a scarce, high-value resource.”

It also stated that “changing the quantity of HEU retained [in the reserve] requires Presidential approval.”[38]

About 1000 tons of 4.5% LEU would be required to fuel the tritium-production reactors for 20 years. If this LEU could be produced by blending down 41 tons of weapon-grade (93.5% U-235) uranium with natural uranium (0.72% U-235) the need for additional unobligated LEU would be delayed until 2060. That is the timeframe when, according to current DOE estimates, more HEU will be required to fuel the naval reactors – or hopefully high-assay LEU if the U.S. and UK nuclear navies can be convinced to design their future propulsion reactors to be fueled with LEU – as French and Chinese propulsion reactors already are.[39]

There is one other requirement for LEU cited in the justification for a new U.S. national enrichment facility, the need for “high-assay LEU for research reactors and test reactors by approximately 2035.”[40] Virtually all of this LEU would be 19.75% enriched. All but a very few research reactors that require refueling[41] are civilian, however.[42] They could be supplied by one of the commercial suppliers.

**Conclusion**

The finding above that the U.S. still has more than 200 tons of weapon-grade uranium available for weapons is firmly based on unclassified information. The finding that about 100 tons of this

WgU is outside the approximately 3,800 U.S. operational warheads, however, depends on the assumption that there is an average of 25 kg of WgU in those warheads. That average is consistent with with all publicly available information but, for no good reason,[43] the actual average is classified. If 25 kg is approximately correct, then there is a real option for the U.S. to delay until 2060 the operation of a new national enrichment plant, at which time it would need to enrich uranium for its naval-propulsion as well as for its tritium-production reactors.

**Appendix: How DOE proposes to fuel the tritium-production reactors until 2040**

In 2016, DOE agreed with TVA that up to 5,000 tritium-producing burnable absorber rods (TPBARs) could be inserted into the fuel assemblies of four designated reactors, two at its Watts Bar and two at its Sequoyah Nuclear Power Plant with up to 2500 in each reactor.[44] DOE did not anticipate a need to use more than a total of 2500 TBARs but, in its 2015 report to Congress, assumed that it would need unobligated, unencumbered LEU fuel for two reactors.

Since that report, tritium requirements appear to have increased, at least temporarily. NNSA now projects that each of the two Watts Bar reactors will be loaded with 1504 TBARs by 2025 for a total of 3008.[45] The TBARs replace neutron absorbers that otherwise would be in the cores. According to the original 1999 Environment Impact Statement on tritium production, operation with less than 2,000 TBARs per reactor core will not increase either the required fuel enrichment level or in the number of fuel assemblies in the core.[46]

Each of the reactors is fueled with LEU enriched to 4.5%, with about 40 tons being replaced every 1.5 years. The plan, as described in DOE's 2015 report to Congress, was that the second reactor, Watts Bar II, would load its first unobligated fuel at the beginning of fiscal year 2018 and would begin tritium production with a completely unobligated core in Fiscal Year (FY) 2021.[47] The two reactors would together require about 50 tons of LEU per year.

In its 2015 report to Congress, DOE described how it had sufficient unobligated LEU to fuel the tritium-production reactors through FY 2027. The details are summarized in Table A.1. DOE then went on to identify additional unobligated LEU and additional HEU that could be blended down to extend the U.S. LEU supply for tritium production until approximately FY2041 (Table A.2).

| Source | Tons of LEU | Reloads | Fiscal Years Loaded |
|---|---|---|---|
| USEC | 20 (4.4%) | 0.5 | 2016 |
| Depleted uranium enrichment | 435 (4.4%) | 10 | 2016-2024 |
| MOX Backup | 173 (4.95%) | 4 | 2025-2027 |

Table A.1. Projected supply of LEU for U.S. Tritium-Production Reactors Through FY 2027.[48]

*LEU supply through FY2027.* The last unobligated uranium produced from natural uranium was enriched by the DOE's Paducah Gaseous Diffusion Plant (GDP) prior to the end of June 2012 and projected to be loaded into the tritium-production reactors in FY 2016. Prior to the shutdown of the GDP in 2013, however, DOE contracted to have an additional 435 tons of LEU produced at Paducah from high-assay depleted uranium (DU).[49] In addition, DOE had down-blended HEU to provide a backup supply of 173 tons of LEU, in case it could not produce mixed-oxide fuel (MOX) from excess plutonium in a timely manner. It now plans to use that LEU for the tritium-production reactors and obtain backup LEU for the MOX fuel, if ever needed, from the commercial market. These supplies of LEU are projected to fuel two TVA reactors through FY2027 (Table A1).

| Source | Tons of LEU | Reloads | Fiscal Years Loaded |
|---|---|---|---|
| Other unobligated LEU | 150 (4.4%) | 3.5 | 2028-2030 |
| Repurposed HEU blend-down | 210 (4.95%) | 5 | 2031-2035 |
| Excess and scrap materials | 400 (4.75%) | 10 | 2035-2041 |

Table A.2. Proposed supply of LEU for U.S. Tritium-Production Reactors Through FY 2041.[50]

*LEU Supply from FY2027-2041.* DOE searched for other possible sources of unobligated LEU and identified 150 tons whose ownership it had transferred TVA and Westinghouse in lieu of payment for blend-down.[51]

In addition, DOE still had excess HEU to blend down. The 175 tons of HEU declared excess to national security needs in 1994, including 22 tons in spent fuel, is considered to be "encumbered" by a commitment to peaceful use but the 20 tons of HEU declared excess in 2005 plus the 8 tons rejected for naval use is considered "unencumbered." In addition, the DOE is reprocessing spent research reactor fuel in Savannah River and blending down the recovered HEU into LEU. The LEU obtained in this way from foreign research reactor fuel is considered obligated to peaceful use but that obtained from U.S. research reactors is not. Based on DOE reprocessing plans as of 2015, four tons of unobligated HEU would become available from planned reprocessing. In addition, in 2015, DOE was launching a Repurposed Excess Uranium Program under which 13.4 tons of HEU, of which 11 tons was unencumbered was to be down-blended to unencumbered LEU. Committing all this material to fuel the tritium-production reactors would result in about 210 tons of unencumbered 4.95% enriched LEU.[52]

Finally, DOE estimated that 400 tons of 4.75% enriched LEU could be obtained from a mix of HEU and HEU material that had not been declared excess for weapons use but that was either less than weapon-grade or in forms that would require considerable processing to be weapon-useable. This 400 tons could fuel the tritium-production reactors from FY2035 to FY2041.[53]

"Most" of the last increment of 400 tons of LEU would come from "national security" HEU that is available for weapons or other uses. The impact on the HEU available for weapons is estimated in the last line of Table 1. "Most" has been translated to an uncertainty range of 50-100%. With regard to enrichment, it has been assumed that the HEU is 50 to 93.5% enriched. The result of the two uncertainty ranges – the 50-100% range for the amount of LEU derived from of HEU available for weapons and the 50-93.5% range for its enrichment – results in an estimated amount of HEU scrap removed from the HEU stockpile available for weapons ranging from 8.7 to 32.7 tons. As shown in the last line of Table 1, this would leave 216.1 to 240.1 tons of HEU available for weapons uses.

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[1] "Opportunity: Q&A for Request for Information for Supply of Enriched Uranium" (U.S. Department of Energy, National Nuclear Security Administration, 16 March 2017) https://www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2fFedConnect%2f%3fdoc%3dDE-SOL-0008552%26agency%3dDOE&doc=DE-SOL-0008552&agency=DOE.

[2] *Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor* (DOE/EIS-0288, March 1999) https://www.nrc.gov/docs/ML0324/ML032460376.pdf. On pp. 5-104, 5-105 it is

stated that, with less than 2000 TBARs in a core, the fuel would be 4.5% enriched and 80 fuel assemblies containing 37 tons of LEU would be required every 1.5 years.

[3] Based on 60,000 SWU per year cited in *Tritium and Enriched Uranium Management Plan Through 2060* (Department of Energy, Report to Congress, October 2015) http://fissilematerials.org/library/doe15b.pdf, p. 36 assuming a depleted uranium assay of 0.25% U-235.

[4] *Tritium and Enriched Uranium Management Plan Through 2060 op. cit.* Table 8 shows a table of naval WgU demand by decade from Fiscal Year 2012 through FY2060. The average annual requirement drops from 3.6 to 2.15 tons/year during that period with an average of 2.5 tons/year.

[5] *Tritium and Enriched Uranium Management Plan Through 2060 op. cit,* pp. 33, 36-39.

[6] See e.g. *Observations on Project and Program Cost Estimating in NNSA and the Office of Environmental Management* (Government Accountability Agency, GAO-13-510T, 2013) https://www.gao.gov/assets/660/654423.pdf.

[7] "Re: Excess Uranium Management: Effects of DOE Transfers of Excess Uranium on Domestic Uranium Mining, Conversion and Enrichment Industries: Request for Information," letter to David Henderson, DOE, from Melissa Mann, URENCO-USA, 22 January 2015, https://www.energy.gov/sites/prod/files/2015/03/f20/29%20-%20Comment%20from%20URENCO%20USA%20Inc.pdf, p. 1.

[8] *NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs*, p. 30.

[9] "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," entered into force Feb. 1, 1995, http://fissilematerials.org/library/1992/07/urenco_treaties_treaty_of_wash.html, Article III.

[10] See the more extensive discussion on this point in *NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs and Improve Technology Cost Estimates* (U.S. Government Accountability Office, GAO-18-126, 2018) https://www.gao.gov/products/GAO-18-126.

[11] The press releases and documents produced as a result of Secretary O'Leary's openness initiative may be found at https://www.osti.gov/opennet/press.jsp.

[12] *Highly Enriched Uranium, Striking a Balance: A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through Sept. 30, 1996,* (U.S. Department of Energy, 2001) http://fissilematerials.org/library/doe01.pdf.

[13] Steven Aftergood and Frank von Hippel, "The U.S. Highly Enriched Uranium Declaration: Transparency Deferred But Not Denied," *Nonproliferation Review* Vol. 14, No. 1, March 2007, pp. 149-161.

[14] *Highly Enriched Uranium Inventory: Amounts of Highly Enriched Uranium in the United States* (U.S. Department of Energy, 2006) update to 30 September 2004. "Transparency in the U.S. Highly Enriched Uranium Inventory" (White House, Office of the Press Secretary, Fact Sheet, 31 March 2016) https://obamawhitehouse.archives.gov/the-press-office/2016/03/31/fact-sheet-transparency-us-highly-enriched-uranium-inventory. For a progress report on the blend-down of excess U.S. HEU, see Charles Irons, "Status of Surplus HEU Disposition in the United States," *Proceedings of the Annual Meeting of the Institute of Nuclear Materials Management, 2016.*

[15] *Highly Enriched Uranium, Striking a Balance, op. cit.,* Table 3-1. U.S. HEU production for weapons ended in 1964 and for naval reactor fuel in 1992, *op. cit.*, pp. 64-65.

[16] Defined as in the possession of DoD (in nuclear weapons and naval-reactor cores), in weapons and components at the DOE's Pantex warhead assembly/disassembly plant, and in DoE's Y-12 facility at Oak Ridge, *Highly Enriched Uranium, Striking a Balance*, *op. cit.* Table 3-1.

[17] "The HEU inventory for the Naval Nuclear Propulsion Program was 100 metric tons of uranium as of September 30, 1996, and was part of the Department of Defense inventory. The majority of HEU assigned to the Naval Nuclear Propulsion Program is already in or has been used in naval reactor cores. The remainder will be fabricated into fuel in the near future." *Highly Enriched Uranium, Striking a Balance, op. cit.* p. 39.

[18] *Highly Enriched Uranium, Striking a Balance*, *op. cit.* Tables 5-1 and 6-1, divides up U.S. HEU production and refeed into four enrichment ranges: 20-70% (95 net tons produced), 70-90% (11.9 tons), 90-96% (580 tons, average enrichment 93.5%), and greater than 96% (163.8 tons, average enrichment 97.4%).

[19] *Highly Enriched Uranium, Striking a Balance, op. cit.* Table 3-3.

[20] Of the 200 tons declared excess, 160 tons were allocated for naval propulsion reactors. Of that 160 tons, 8 tons were rejected by the nuclear Navy as not up to its specifications and added to the HEU to be blended down, "Status of Surplus HEU Disposition in the United States," *op. cit*, Slide 4. Of the remaining 40 tons, 20 were committed to be used by HEU-fueled research and space reactors and 20 for blend-down to LEU for civilian power and research reactors.

[21] It is assumed that the material accepted by the navy is weapon-grade.

[22] At one end of the range, the material committed to be blended down is assumed to have the average enrichment of the non-naval military stockpile after removal of 152 tons of weapon-grade uranium. At the other end, it is assumed that, after the 200 tons was declared excess, the remaining stockpile available for weapons is weapon-grade.

[23] If this stock were a mix of weapon-grade and 50% HEU, the 50% HEU would amount to 36.1 tons.

[24] See Appendix.

[25] "Remarks Prepared for Energy Secretary Sam Bodman," 2005 Carnegie International Nonproliferation Conference, Washington, DC, November 7, 2005, https://www.energy.gov/articles/2005-carnegie-international-nonproliferation-conference. For the background to the warhead-reduction announcement that preceded this declaration, see Robert S. Norris and Hans M. Kristensen, "What's Behind Bush's Nuclear Cuts?" *Arms Control Today*, October 2004, https://www.armscontrol.org/print/1667.

[26] *Tritium and Enriched Uranium Management Plan Through 2060*, *op. cit.* p. 27. In Table 8, the report shows the projected rate of use by naval reactors by decade, starting in fiscal year (FY) 2012. The total projected use during FY 2012-2060 is 128.3 tons. The website of DOE's Y-12 facility states that it began providing HEU for naval reactors starting in FY2002, http://www.y12.doe.gov/news/report/nuclear-navy. It is not clear, however, how much of the 160 tons was used before FY2012.

[27] *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* Figure 2. In addition to the 102.8 tons of HEU declared excess from the weapons stocks, President Clinton declared surplus 75.6 tons of HEU located at DOE sites other than Y-12 and Pantex.

[28] *Highly Enriched Uranium Inventory* (2006), *op. cit.* Table 1 and *Highly Enriched Uranium, Striking a Balance* (2001) Table 3-3. The other four DOE sites with HEU that was not declared excess were: the Idaho National Laboratory (5 tons) where irradiation tests are done on naval reactor fuel in a research reactor fueled with HEU and co-located with an HEU-fueled critical assembly; the Los Alamos nuclear weapons laboratory (2.9 tons) from which HEU used in criticality measurements was subsequently shipped to the high-security Device Assembly Facility (DAF) on the Nevada National Security Site (formerly the Nevada [Nuclear Weapons] Test Site); Sandia National Nuclear Laboratory (0.5 tons) from which the HEU-fueled Sandia Pulsed Reactor was subsequently also shipped to the DAF; and "other" sites (1.9 tons) which would presumably include the Navy's contractor-operated reactor-design laboratories and fuel-fabrication facilities.

[29] See e.g. "Megatons to Megawatts," Centrus, http://www.centrusenergy.com/who-we-are/history/megatons-to-megawatts/. Centrus is the post-bankruptcy name for the U.S. Enrichment Corporation, which acted as the agent for the U.S. government in purchasing the Russian LEU.

[30] The U.S. stock of military non-naval HEU before the first declaration of excess in 1994 was 552 tons (Table 1 above). The U.S. stockpile of operational weapons during the 1980s before the Soviet disintegrated in 1991 averaged about 23,000, U.S. Department of Defense Fact Sheet**, "**Increasing Transparency in the U.S. Nuclear Weapons Stockpile ," 3 May 2010, https://www.defense.gov/Portals/1/features/defenseReviews/NPR/10-05-03_Fact_Sheet_US_Nuclear_Transparency__FINAL_w_Date.pdf. The ratio is 24 kg. Note, however, that the average enrichment was about 83%, which is less than U.S. weapon-grade (93.5% U-235).

[31] The exact number of U.S. operational warheads as of 30 September 2017 was 3822, Hans Kristensen, "Despite Rhetoric, US Stockpile Continues to Decline," https://fas.org/blogs/security/2018/03/stockpile-reduction/

[32] Hans M. Kristensen and Robert S. Norris, "US nuclear forces, 2018," *Bulletin of the Atomic Scientists*, https://thebulletin.org/nuclear-notebook. The reserve is given as 2200 as of the end of 2016 but the total was reduced by about 200 as of the end of 2017.

[33] There were about 2,800 retired warheads awaiting dismantlement as of the end of FY 2016, "Remarks by the Vice President [Biden] on Nuclear Security" 11 January 2017, https://obamawhitehouse.archives.gov/the-press-office/2017/01/12/remarks-vice-president-nuclear-security. This number was decreased by 354 warheads dismantled during FY2017 and increased by the 196 warheads retired during FY2017, Hans Kristensen, "Despite Rhetoric, US Stockpile Continues to Decline," *op. cit*, for a net reduction of 158.

[34] *Nuclear Weapons Council: Enhancing Interagency Collaboration Could Help with Implementation of Expanded Responsibilities* (Government Accountability Office, 2015) https://www.gao.gov/assets/680/670385.pdf.

[35] "Bush Pushed for Nuclear Cuts, Rep. Says," 13 August 2004, http://www.nti.org/gsn/article/bush-pushed-for-nuclear-cuts-rep-says/ gives background and links on the successful effort, led by Representative David Hobson to force the G.W. Bush Administration to reduce the number of warheads in the U.S. stockpile from 11,000-10,000 during 1994-2003 to 5,000-4,000 during 2011-2016 following the conclusion of the Strategic Offensive Reductions Treaty, which reduced the number of deployed strategic warheads from the START level of about 6,000 to about 2,000.

[36] *Nuclear Weapons:Actions Needed by NNSA to Clarify Dismantlement Performance Goal* (Government Accountability Office, 2014) https://www.gao.gov/assets/670/662840.pdf, p. 41.

[37] *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* p.18.

[38] *Tritium and Enriched Uranium Management Plan Through 2060*, *op. cit.* pp. 18-19.

[39] Frank von Hippel, *Banning the Production of Highly Enriched Uranium* (International Panel on Fissile Material, 2016) http://fissilematerials.org/library/rr15.pdf.

[40] "Opportunity: Q&A for Request for Information for Supply of Enriched Uranium," *op. cit.*

[41] A significant fraction of all research reactors are critical assemblies, pulsed reactors or very low power reactors that have lifetime cores.

[42] The U.S. has one high-power reactor, the Advanced Test Reactor, that is used for irradiation tests of naval-propulsion reactor fuel. It also has a high-power naval prototype reactor that is used to test naval cores. Both reactors are fueled with HEU. All other U.S. research reactors that require refueling are civilian, IAEA, Research Reactor Database.

[43] "Detailed judgments for updating weapon design classification guidance are given in Appendix D [classified]. Little change is recommended except in the area of the association of materials with weapons in general or, in some cases, with specific weapons. Declassifying these associations, even if estimates of the mass used in specific weapons can be inferred from plant feed streams or averages, is considered of small risk as long as the details of how the materials are used are protected," *Report of the Fundamental Classification Policy Review Group* (Department of Energy, 15 January 1997, Unclassified Version) chapter 4, https://fas.org/sgp/library/repfcprg.html.

[44] DOE/NNSA, "Production of Tritium in Commercial Light Water Reactors," Record of Decision, 22 June 2016, https://www.federalregister.gov/documents/2016/06/22/2016-14775/production-of-tritium-in-commercial-light-water-reactors.

[45] *Fiscal Year 2018 Stockpile Stewardship and Management Plan: Report to Congress* (Department of Energy, November 2017) https://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/fy18ssmp_final_november_2017.pdf, Figure 2-11.

[46] *Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Re*actor, *op. cit*, p. 5-104 and Table 5-53.

[47] *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* Figure 5.

[48] *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* Table 1 and Figure 5.

[49] Today, the amount of U-235 left in depleted uranium from enrichment in the U.S. and Europe is about 0.22%, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/uranium-and-depleted-

uranium.aspx. A considerable portion of the depleted uranium associated with early U.S. HEU production contain more than 0.34% U-235 and DOE judged that it would be worthwhile to feed them through an enrichment plant again, *Excess Uranium Inventory Management Plan: Report to Congress* (Department of Energy, 2013) https://www.energy.gov/sites/prod/files/2013/07/f2/Excess%20Uranium%20Inventory%20Management%20Plan.pdf.

50 *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* pp. 15-18.

51 *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* Table 2 and Figure 5.

52 *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* pp. 15-16, Figure 5.

53 *Tritium and Enriched Uranium Management Plan Through 2060, op. cit.* pp. 16-18, Figure 5.