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Consistency Tests for the Declarations of U.S. Fissile-Material Production

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In the 1970s and early 1980s, the United States Government released data on the history of its purchases of natural uranium, the amount of separative work done by U.S. uranium enrichment plants, and the fission energy released by U.S. production reactors. These data provided the basis of nongovernmental estimates in the 1980s of U.S. production of plutonium and highly enriched uranium. In 1996 and 2006, the United States published reports on its historical production of plutonium and highly enriched uranium respectively. This article presents a first rough analysis of the two sets of data and finds that they are reasonably consistent.

The United States was the first country to produce highly enriched uranium (HEU) and plutonium for weapons. In 1996 and 2006, it published official reports on its historical production and use of these materials, based on data in the national Nuclear Material Management and Safeguards System:

- Highly Enriched Uranium: Striking a Balance,[1] and
- Plutonium: The first 50 years.[2]

The sites at which the U.S. produced HEU and separated plutonium for military purposes are shown in Figure 1.

According to the HEU declaration, cumulatively, the United States produced at Oak Ridge, Tennessee and Portsmouth, Ohio a net of about 850 tons of HEU containing about 750 tons of uranium-235. Production of HEU for weapons ended in 1964 just before the U.S. nuclear-warhead stockpile peaked at over 30,000 weapons.[3] Subsequently, each generation of U.S. nuclear warheads used HEU recycled from the previous generation. Additional HEU,

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Figure 1: U.S. HEU and plutonium production sites.

enriched to more than 96 percent in uranium-235, was produced for naval-reactor fuel, however, through 1992. The availability of huge quantities of weapon-grade uranium from excess Cold War weapons then made unnecessary further production of HEU for this purpose as well.

According to the plutonium-production declaration, the nine U.S. plutonium-production reactors at the Hanford site in Washington State produced cumulatively 67 tons of plutonium and the five reactors at the Savannah River site in South Carolina 36 tons. Production peaked in 1964. Nine of the fourteen production reactors were shut down between 1964 and 1971. The last was shut down in 1988.

This article reports the positive results of rough consistency checks of the U.S. HEU and plutonium-production declarations with information released by the U.S. Government in the 1970s and early 1980s, respectively, the:

- Annual enrichment work done in the U.S. enrichment complex, and the
- Fission heat generated annually by U.S. production reactors.

It also reports good consistency between the amount of uranium purchased by the U.S. Government during the period 1944–71 and the calculated quantities of uranium-235 required for the reported production of HEU and plutonium, if the reported residual stocks of natural and low-enriched uranium at the end of the Cold War are taken into account.

These consistency checks are derived from non-governmental estimates of U.S. HEU and plutonium production done in the 1980s, long before the government declarations became available.[4]

Highly Enriched Uranium (HEU)

Natural uranium contains about 0.72 percent of the chain-reacting isotope uranium-235 mixed with non-chain-reacting uranium-238. Uranium "enriched" to more than 20 percent in uranium-235 is considered weapon-usable and is designated "highly enriched uranium" or HEU. HEU was first produced for the Hiroshima bomb, which contained about 60 kg of uranium enriched to 80 percent.

During 1945–47, a little over a ton of HEU was produced by electromagnetic separation at the Manhattan Project's Y-12 plant near Oak Ridge, Tennessee. The focus of U.S. HEU production shifted quickly, however, to two huge gaseous diffusion plants (GDPs), one at Oak Ridge, Tennessee and one at Portsmouth, Ohio (Table 1).[5]

The Oak Ridge GDP, whose construction began during World War II, produced HEU for weapons until 1964 when the U.S. stockpile of warheads peaked. Thereafter, it produced only low-enriched uranium for nuclear power plant fuel until 1985.

The Portsmouth GDP started production in 1956 and also ended HEU production for weapons in 1964. However, it began to produce HEU that was even more highly enriched, to an average of 97.4 percent, for naval-propulsion reactor fuel. Cumulatively, 164 tons of this super-grade uranium was produced for naval-reactor fuel at a net average rate of about 6 tons per year. This ended in 1992, when huge quantities of excess weapon-grade HEU (greater than 90 percent enriched) became available from the first post-Cold War downsizing of the U.S. weapons stockpile. Future U.S. naval reactors are being designed to be fueled with this uranium.[6]

Table 1: The enrichment plants that produced U.S. HEU. Source: U.S. Department of Energy, "Highly Enriched Uranium: Striking a Balance."

Site	Isotope Separation Technology	Period of HEU Production	Peak Annual Production (uranium-235 in HEU)
Oak Ridge, Tennessee	Electromagnetic	1945–47	About 1 ton but mostly re-fed
Oak Ridge, Tennessee	Gaseous diffusion	1945–64	37 tons/yr in 1958–62
Portsmouth, Ohio	Gaseous diffusion	1956–92	39 to 40 tons/yr in 1960–62

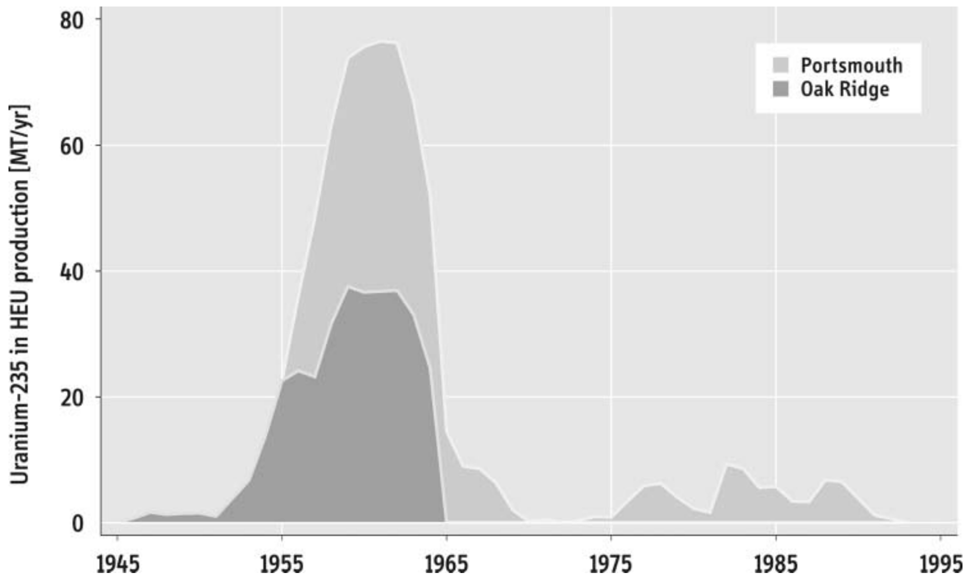

Figure 2: History of net U.S. production of HEU by site (tons/year uranium-235 content). The data are stacked, i.e., the upper curve is the total HEU production. Based on U.S. Department of Energy, "Highly Enriched Uranium: Striking a Balance."

Figure 2 shows the history of declared net U.S. HEU production, measured by its contained uranium-235 by site and by year. The HEU is measured by its uranium-235 content because that determines the value of the HEU and also is a good measure of the separative work that was required to produce the HEU.[7]

Consistency with Historical Separative Work

In the 1970s and early 1980s, the U.S. government made public the history of annual enrichment work done by the U.S. enrichment complex and the amount of uranium-235 left in the associated depleted uranium (Figure 3).[8] Shown also in Figure 3 is the amount of enrichment work that would be required to account for the annual HEU production reported in "Highly Enriched Uranium: Striking a Balance," plus the small requirements for re-enriching the fuel used for annual U.S. plutonium production as reported in "Plutonium: The first 50 years." The calculations are approximate, most importantly because U.S. HEU production and re-feed have been approximated as two streams with average enrichments in the ranges 20–70 and 70–100 percent. It will be seen, however, that the match is reasonably good until about 1964, when the United States began to produce large quantities of low-enriched uranium for power reactors.

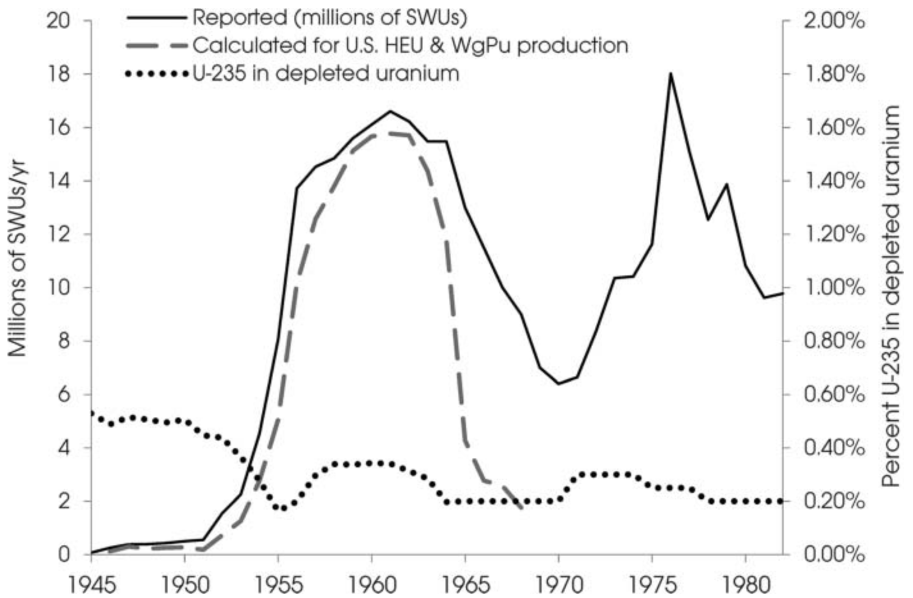

Figure 3: U.S. reported historical enrichment work and the amount that can be accounted for by U.S. production of HEU and re-enrichment of natural uranium used to fuel plutonium-production reactors. Source for historical and enrichment work and depleted uranium essay: James H. Hill and Joe W. Parks, U.S. Energy Research and Development Administration.

Plutonium

The first significant quantities of plutonium produced in the United States were used in the nuclear explosive that was tested in New Mexico on 16 July 1945 and the bomb based on that design that was detonated over the Japanese city of Nagasaki on 9 August 1945. This plutonium was produced by the first three graphite-moderated, water-cooled reactors built on what is now the Department of Energy's (DOE's) Hanford site on the Columbia River in Washington State. An additional six such graphite-moderated production reactors were later built at Hanford and five productions reactors moderated and cooled by heavy water were built on the Savannah River Site in South Carolina (Table 2 and Figure 4).[9] In addition to plutonium, the Savannah River reactors were used to produce tritium, the 12-year half-life heavy hydrogen isotope used to "boost" the yield of the fission triggers in modern weapons.[10]

Eight of the nine Hanford production reactors were shut down permanently between 1964 and 1971—the period during which the U.S. nuclear stockpile peaked. The Hanford N-reactor continued to operate during 1971–82, primarily to produce electric power, with fuel-grade plutonium for the U.S. breeder-reactor program as a byproduct. In 1983, in response to plans by the Reagan Administration to increase the size of the U.S. stockpile, the N-reactor

Table 2: U.S. production reactors and their periods of operation. Source: U.S. Department of Energy: "Plutonium: The first 50 years."

Hanford Site	Dates of operation	Savannah River Site	Dates of operation
B-reactor	1944–68	R-reactor	1953–64
D-reactor	1944–67	P-reactor	1954–88
F-reactor	1945–65	K-reactor	1954–92
H-reactor	1949–65	L-reactor	1954–88
DR-reactor	1950–64	C-reactor	1955–85
C-reactor	1952–69		
KW-reactor	1955–70		
KE-reactor	1955–71		
N-reactor	1963–87		
Peak site plutonium production rate: 5.3 tons (1965)		2.1 tons (1964)	

was shifted back to producing weapon-grade plutonium but was shut down in 1987, after the 1986 Chernobyl accident provoked concerns about its lack of an accident-containment building.[11] Four of the five Savannah River reactors continued to operate into the 1980s primarily to produce tritium. Today, tritium for U.S. nuclear weapons is produced in power reactors.[12]

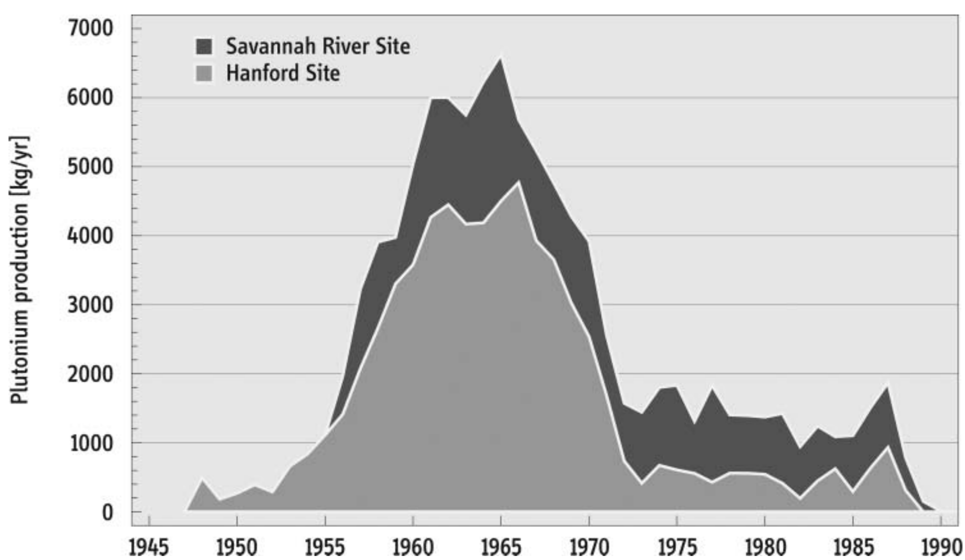

Figure 4: Declared historical production of U.S. plutonium at the two U.S. plutonium-production sites. The data are stacked, i.e., the upper curve is the total plutonium production. Source: U.S. Department of Energy: "Plutonium: The first 50 years."

All of the plutonium produced by the Savannah River reactors was "weapon-grade" (relatively pure plutonium-239 containing less than 7 percent plutonium-240), but 12.9 tons of the Hanford plutonium was not weapon-grade. This includes 4 tons of plutonium that was never recovered from irradiated N-reactor fuel.

The Hanford reactors were used to produce on the order of a ton of uranium-233 and some tritium on an experimental basis,[13] but the great preponderance of their output was plutonium. The Savannah River reactors were fueled much of the time by HEU "driver fuel" and were used to produce tritium as well as plutonium. They also produced smaller amounts of uranium-233, americium-242, curium-244, polonium-210, cobalt-60, plutonium-238, plutonium-242, and californium-252.[14]

Consistency with Historical Fission-heat Production

In the mid-1980s, the Department of Energy published data on the thermal output of the Hanford and Savannah River production reactors for the period 1951–1971 and T. B. Cochran et al., in U.S. *Nuclear Warhead Production*, obtained from the DOE data for 1955–1984. This information can now be compared with the annual plutonium production figures reported in "*Plutonium: The First 50 Years*." It has been assumed that the plutonium production is associated with the reactor power output half a year earlier, i.e., that cooling of the irradiated uranium and reprocessing took six months. Figure 5 shows the ratio of reported cumulative production of weapon-grade production to the

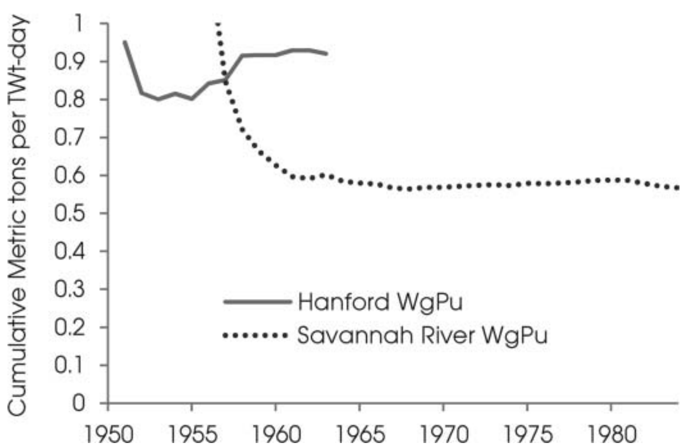

Figure 5: Cumulative production of plutonium divided by cumulative fission heat release for the first eight Hanford production reactors during 1944–1963 and the Savannah River reactors during 1955–84. It has been assumed that the plutonium was separated six months after being produced. The large ratio early on for the Savannah River reactors is probably an artifact associated with the inaccuracy of this assumption, which has only a small effect in later years. Source: Author's calculations.

reported cumulative fission heat output for the Hanford and Savannah River production reactors as a function of time during these periods. The ratio becomes more insensitive to the assumed time delay as one moves to the right, i.e., as the cumulative sums in the numerator and the denominator cover more years. At the latest dates shown, the ratios for the original eight Hanford reactors in 1963[15] and the Savannah River Reactors in 1984 settle down respectively to about 0.9 tons and 0.57 tons of plutonium per terawatt-day (TWt-day) of heat produced.

Glaser has calculated that 0.87 tons of weapon-grade plutonium containing 94 percent plutonium-239 would be produced per TWt-day in the Hanford reactors.[16] The cumulative ratio for the production of weapon-grade plutonium shown in Figure 5 for Hanford in 1963 is reasonably close to his estimate.[17] The plutonium production rate of the Savannah River reactors should be comparable. The fact that their cumulative plutonium production was lower by about 0.3 tons per TWt-day is due primarily to the fact that a large fraction of their excess neutrons were used instead for the production of tritium.[18]

Uranium Purchases

Figure 6 shows U.S. Government purchases of natural uranium by year. A total of 250,000 metric tons of uranium containing about 1800 tons of uranium-235 was purchased.[19]

The United States ended the Cold War with some of the uranium-235 in unused natural and low-enriched uranium. In 1985, a DOE official testifying

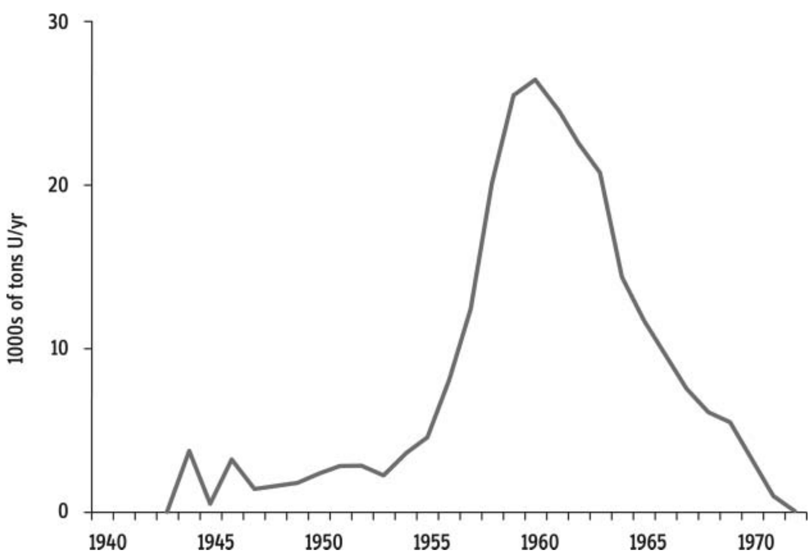

Figure 6: U.S. Government purchases of natural uranium. Source: T. B. Cochran et al.

on U.S. enrichment operations stated that the department had an inventory of natural and enriched uranium equivalent to 41,600 tons of natural uranium and 16.5 million separative work units (SWU).[20] The natural uranium equivalent would have contained about 300 tons of uranium-235. The DOE went on, however, to produce during the period 1986–1992, HEU containing 34 tons of uranium-235, which would have been accompanied by 18 tons of Uranium-235 in depleted uranium, assuming a depleted uranium assay of 0.25 percent.[21] This would leave about 250 tons of Uranium-235, equivalent to 35,700 tons of natural uranium, in DOE's inventory. This inventory was later mostly sold or given to the U.S. Enrichment Corporation (USEC).[22]

In addition to this stockpile of natural and low-enriched uranium (LEU) at its uranium-enrichment facilities, the DOE ended the Cold War with a stockpile of natural and low-enriched uranium in the fuel cycles of the Hanford and Savannah River production reactors. Of this material, 2,159 tons of the LEU was at DOE's shutdown Fernald (Uranium) Feed Materials Production Center (2,155 tons in the enrichment range of 0.82 to 1.25 percent and 4 tons averaging about 5 percent enriched) and 1,462 at the DOE's Hanford plutonium production site (865 tons with an enrichment of 0.95–1.25 percent, 450 tons with an average enrichment of 0.86 percent, and 147 tons of natural uranium).[23] This uranium therefore contained an additional 35 tons of uranium-235. Also, assuming that the 2,100 tons of spent N-reactor fuel at Hanford had an average enrichment of one percent, it would contain about 20 tons of uranium-235. The total amount of uranium-235 in these plutonium-production reactor fuel cycle residuals therefore would be about 55 tons. This information is summarized in the top of Table 3.

Table 3: Uranium-235 acquired by the U.S. Government in natural uranium less the amount remaining in natural and low-enriched uranium at the end of the Cold War compared with the estimated amount required for HEU and plutonium production (metric tons).

Acquired	1800
Remaining in natural and low-enriched uranium	
in the production-reactor fuel cycle	55
in the enrichment complex	250
Net amount used	1495
Requirements	
In HEU product	750
Consumed in natural and slightly-enriched production-reactor fuel	100
In depleted uranium	
from HEU production	550
from production of natural and slightly-enriched production-reactor fuel	69
Total requirements	1469

Table 3 also provides estimates of the U.S. requirements of uranium-235 for HEU and plutonium production and the estimated associated amounts of uranium-235 in depleted uranium. The agreement between the amount acquired and the amount used is better than should be expected, given the uncertainties involved. Below, we provide the basis for the entries in Table 3 listed under "requirements."

In HEU Product

We have seen above that 750 tons of uranium-235 ended up in U.S. HEU.

Consumed in Natural and LEU-fueled Plutonium Production Reactors

The nine Hanford reactors produced 54.5 tons of weapon-grade (and 12.9 tons of fuel-grade) plutonium. If we use the production rate of 0.9 tons of plutonium per TWt-day for weapon-grade plutonium (0.7 tons for fuel-grade plutonium),[24] the associated release of fission heat would have been about 60 (18 TWt-days). About 5 (3) TWt-days of this fission heat would be from the fission of plutonium-239.[25] Assuming one ton of fission per TWt-day, the amount of uranium-235 fission in weapon-grade (fuel-grade) plutonium production then would be 55 (15) tons. Taking into account the fact that 0.18 atoms of uranium-235 are converted to uranium-236 for every atom of uranium-235 fissioned, the total amount of uranium-235 consumed in producing the Hanford weapon-grade and fuel-grade plutonium would have been about 80 tons.

The uranium-235 consumed in HEU fuel in the Savannah River production reactors is already included in the HEU production above. The Savannah River reactors were fueled with natural or low-enriched uranium, however, during plutonium-production campaigns until 1968,[26] by which time they had produced 17.4 tons of weapon-grade plutonium. Assuming a production rate of 0.9 tons of plutonium per TWt-day, this would account for the consumption of an additional 18 tons of uranium-235.

The total amount of uranium-235 consumed in natural and slightly enriched uranium during the production of U.S. plutonium would therefore have been about 100 tons.

In Depleted Uranium

Much of the uranium-235 in the natural uranium bought by the United States went into depleted uranium.

From HEU Production. With the historical net production of HEU and the historical assay of depleted uranium shown in Figure 3, the amount of uranium-235 in depleted uranium associated with U.S. HEU production would be 550 tons.

From the Enrichment of Natural and Slightly Enriched Production-reactor Fuel. For the production of weapon-grade plutonium containing 5 percent

Plutonium-240 in a graphite-moderated reactor, natural-uranium-fuel is irradiated until about 700 MWt-days of fission energy have been released per ton of uranium.[27] As noted, about 0.9 metric tons of weapon-grade plutonium were produced per TWt-day of fission-energy release (Figure 5). Approximately 1 TWt-day of energy is released per ton of uranium-235 and plutonium-239 fissioned and approximately 0.18 tons of uranium-235 is converted to uranium-236 for every ton of uranium-235 fissioned. However, some of the fission is of plutonium. For every plutonium-239 atom that captures a neutron and becomes plutonium-240, about two plutonium-239 atoms fission.[28] Taking all these considerations into account, for every ton of weapon-grade plutonium produced, about 1600 tons of uranium would have been irradiated and its enrichment would have been reduced by 0.08 percent. Assuming that the uranium was re-enriched up to 0.72 percent and using the historical U.S. depleted-uranium assay at the time (Figure 3), about 6 million SWUs of enrichment work would have been required and an additional 64 tons of uranium-235 would have ended up in depleted uranium as a result of the re-enrichment of the irradiated uranium from production of 54.5 tons of weapon-grade plutonium at Hanford plus the 17.4 tons at Savannah River produced through 1968, before the Savannah River reactors were fueled with HEU.[29]

With regard to the production of fuel-grade plutonium, T. B. Cochran et al. state that the N-reactor fresh fuel had an average enrichment of about 0.99 percent Uranium-235 and, when operating in the fuel-grade-plutonium production mode, the average discharge enrichment was 0.77 percent.[30] This corresponds to a fission energy release of 1.9 MWt-days/kg and the production of 1.44 grams of plutonium per kg.[31] Re-enriching the fuel to 0.99 percent for an average depleted uranium assay of 0.23 percent uranium-235 would result in 0.3 atoms of uranium-235 ending up in the depleted uranium per Uranium-235 atom consumed and therefore about 5 tons of Uranium-235 in the associated depleted uranium.

NOTES AND REFERENCES

1. U.S. Department of Energy, "Highly Enriched Uranium: Striking a Balance. A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996," Draft, Rev. 1., January 2001 (publicly released in 2006) <www.ipfmlibrary.org/doe01.pdf>.

2. U.S. Department of Energy, "Plutonium: The First 50 Years: United States Plutonium Production, Acquisition and Utilization from 1944 through 1994," DOE/DP-0137 (1996) <www.ipfmlibrary.org/doe96.pdf>.

3. Robert L. Morgan, Deputy Assistant Secretary for Defense Programs, Department of Energy, in *Energy and Water Developments Appropriations for 1985*, Hearings before the Subcommittee on Energy and Water Development of the House Committee on Appropriations, 13 March 1984, pp. 346–347.

4. Frank von Hippel, David Albright, and Barbara G. Levi, "Quantities of Fissile Materials in U.S. and Soviet Nuclear Weapons Arsenals," Princeton University,

Report PU/CEES 168 (1986) http://www.fissilematerials.org/ipfm/site_down/hip86.pdf. Thomas B. Cochran, William M. Arkin, Robert S. Norris, and Milton M. Hoenig. *Nuclear Weapons Databook. Vol. 2, U.S. Nuclear Warhead Production* (Cambridge, MA: Ballinger, 1987).

5. A third gaseous diffusion plant, in Paducah, Kentucky, which was still operating in 2010, produced only low-enriched uranium, but was part of the HEU-production complex because it re-enriched depleted uranium from the other two plants. "Highly Enriched Uranium: Striking a Balance," *op. cit.* Production from Tables 5.2, 5.3, 5.4 minus HEU re-fed from Tables 6.2, 6.3 and 6.4.

6. Department of Energy, "FY 2009 Congressional Budget Request," Volume 1, DOE/CF-024, p. 550.

7. Based on "Highly Enriched Uranium: Striking a Balance," *op. cit.*, Tables 5-1, 5-3, 6-2, 6-3 and 6-4. The United States produced HEU containing about 102 tons of Uranium-235, enriched to less than 90 percent. Of this, HEU containing 60 tons of Uranium-235 was re-fed into the enrichment plants. Fifty-eight tons of weapon-grade uranium (>90 percent enriched) also was re-fed. The amount of enrichment work required to produce HEU containing a kilogram of uranium-235 depends only weakly on the HEU's enrichment. It depends more on the associated assay of the depleted uranium "tails." For HEU enrichments from 20 to 99 percent uranium-235, the SWU requirements per kg of uranium-235 in the HEU rise from 192 to 218 for 0.1 percent uranium-235 in the tails, from 229 to 256 for 0.2 percent tails and 299 to 325 for 0.3 percent tails.

8. A SWU is a kilogram separative work unit. The SWU-equivalent of the HEU is calculated separately based on the average enrichment of the net HEU produced with greater and less than 70 percent enrichment during that year. This approximation breaks down after 1968—most notably in 1969, 1970, 1971, 1974 and 1976—when the enrichment of the material with enrichment greater than 70 percent is calculated to be greater than 100 percent. These are years when the HEU re-feed to Portsmouth was comparable to or greater than its gross HEU output and finer divisions of HEU inputs and outputs by enrichment intervals would be required. U.S. historical SWU production, 1945–1971: James H. Hill and Joe W. Parks, U.S. Energy Research and Development Administration, "Uranium Enrichment in the United States," CONF 750324-7, Fig. 1. "1971–1982: Uranium Enrichment 1980 and 1982 Annual Reports," U.S. DOE, Oak Ridge Operations Office), reported in T. B. Cochran et al., *op. cit.,* pp. 85 and 184.annual U.S. HEU production by enrichment range from "Highly Enriched Uranium: Striking a Balance," *op. cit.*, Tables 5.1, 6.2, 6.3 and 6.4.

9. "Plutonium: The First 50 Years*," op. cit.,* pp. 25, 30 (Table 2) and Tables 2, 3 (Figure 4).

10. In modern nuclear-warhead designs, the fusion of a few grams of tritium with deuterium is used to generate neutrons during the initial fission explosion to create an extra burst of neutrons that cause extra fissions and thereby "boost" the fission yield of the "primary." Early in the U.S. "hydrogen-bomb" development project, it was believed that large amounts of tritium might be required to ignite the fusion of deuterium nuclei in the thermonuclear second stage, Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb* (New York: Simon and Schuster, 1995). Later, it was realized that tritium could be made during the explosion by neutron capture on lithium-6.

11. Congress scaled back the Reagan Administration's plans considerably and the U.S. stockpile increased by only about 700 warheads between 1982 and 1987, "Increasing Transparency in the U.S. Nuclear Weapons Stockpile," U.S. Department of Defense Fact Sheet, May 3, 2010.

12. Tritium for U.S. nuclear weapons is currently produced in government-owned nuclear-power reactors operated by the Tennessee Valley Authority, U.S. Nuclear

Regulatory Commission, "Fact Sheet on Tritium Production," May 2003, <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/tritium.html>.

13. 640 kg of uranium-233 was authorized to be produced during 1969 and 1970, internal Atomic Energy Commission telegram dated 29 January 1968, <http://www5.hanford.gov/ddrs/common/findpage.cfm?AKey = D199020827>. Tritium production with slightly enriched fuel was discussed by D.W. Peacock et al., "2.1 enriched uranium-lithium loading memorandum—fuel and target performance," 24 July 1967, <http://www5.hanford.gov/ddrs/common/findpage.cfm?AKey = D1344939>.

14. "Plutonium: The First 50 Years," *op. cit*., p. 30.

15. In 1964, the Hanford reactors began to produce fuel-grade as well as weapon-grade plutonium and only fuel-grade plutonium was produced during 1972–82.

16. International Panel on Fissile Materials (IPFM)," Global Fissile Material Report 2010, Balancing the Books: Production and Stocks," Appendix B, Production of Highly Enriched Uranium and Plutonium for Weapons, p. 155, <http://www.fissilematerials.org/ipfm/site_down/gfmr10.pdf>.

17. Annual figures for fission heat from the Hanford and Savannah River production reactors from T. B. Cochran et al., *op. cit.*, Tables 3.2, 3.3 and 3.4. Annual plutonium production at the Hanford and Savannah River sites from "Plutonium: The First 50 Years," *op. cit*., Tables 2, 3. A huge amount of additional material on the operations of the Hanford reactors has been declassified. See <http://www2.hanford.gov/declass/>.

18. If it is assumed that, in the absence of the production of other radioisotopes, the Savannah River reactors would have produced 0.87 tons of plutonium per TWt-day, and that 1/72 grams of tritium is produced per gram of plutonium not produced (T. B. Cochran et al., *op. cit.* p. 180, footnote 4) then an average of about 7.5 kg of tritium would have been produced per year during the period 1970–84. Assuming that the production during that period was primarily makeup tritium to balance decay associated with tritium's 12.1-year half-life, this would correspond to an equilibrium inventory of about 130 kg of tritium in the early 1980s or an average of about 6 grams per warhead at a time when there were about 23,000 nuclear warheads in the U.S. stockpile, "Increasing Transparency in the U.S. Nuclear Weapons Stockpile," *op. cit.*

19. T. B. Cochran et al., *op. cit.*, Table 3.17. The data on U.S. acquisitions of natural uranium during the period 1956–71 also can be found in *Statistical Data of the Uranium Industry* (U.S. Department of Energy, Grand Junction Area Office, Colorado) GJ0–100 (33).

20. "DOE Says It Will Not Need to Buy Uranium," *Nuclear Fuel*, May 20, 1985.

21. Reportedly, in 1985, the Portsmouth enrichment plant, the only plant producing HEU at the time, was operating with this assay, "DOE Says It Will Not Need to Buy Uranium," *op. cit.*

22. USEC took over the operation of the Government's remaining gaseous diffusion enrichment plants at Paducah, Kentucky and Portsmouth, Ohio in 1998. In 1998, DOE transferred to USEC 10,800 tons of natural uranium and the equivalent of 453 tons in LEU, "Natural Uranium and HEU from DOE," *Nuclear Fuel*, July 13, 1998. A 1996 Environmental Assessment states that the DOE had declared excess for sale 7,800 tons of natural uranium and 460 tons of 4.5 percent enriched LEU, U.S. Department of Energy, Environmental Assessment, "DOE Sale of Surplus Natural and Low Enriched Uranium," DOE/EA-1172, October 1996. At a depleted uranium assay of 0.3 percent associated with the production of the LEU, this would correspond to a total of 12,400 tons of natural uranium. In 2008, DOE announced that it had 5,156 tons of excess U.S. origin natural uranium in the form of hexafluoride, U.S. Department of Energy, "Excess Uranium Inventory Management Plan," December 16, 2008, Appendix B http://www.ne.doe.gov/pdfFiles/inventory_plan_unclassified.pdf. The total of

all the above dispositions are the equivalent of 28,800 tons of natural uranium, containing about 200 tons of uranium-235. In addition, USEC had an inventory equivalent to 12,145 of natural uranium before the DOE transfers, "Natural Uranium and HEU from DOE," *op. cit.* Most of this material was presumably from its customers but a working inventory must have come with the plants. The combined capacity of the Paducah and Portsmouth plants was about 20 million SWUs. The working inventory inside the cascades would have been on the order of 2,000 tons, Allan S. Krass. *Uranium Enrichment and Nuclear Weapon Proliferation* (New York: International Publications Service, Taylor & Francis, 1983), p. 127. USEC estimated that it would require an operational inventory of 5,000 tons, "Natural Uranium and HEU from DOE," *op. cit.*

23. "DOE Seeks Interest in Surplus Uranium, SWU at Fernald, Hanford Sites," *Nuclear Fuel*, April 13, 1992.

24. For the production of weapon-grade plutonium, we use the ratio derived in Figure 5. For the production of fuel-grade plutonium, we extrapolate to a burnup that would produce plutonium containing 85 percent plutonium-239 from Alexander Glaser, "Isotopic Signatures of Weapon-Grade Plutonium from Dedicated Natural Uranium-Fueled Production Reactors and Their Relevance for Nuclear Forensic Analysis," *Nuclear Science and Engineering* 163 (2009).

25. Assuming that weapon-grade and fuel-grade plutonium are 5 percent and 12 percent plutonium-240 respectively. T. B. Cochran et al., *op. cit.*, Table 3.4, shows the N-reactor producing fuel-grade plutonium with nominally 9 and 12 percent plutonium-240 for eight years each. In addition, there was a small amount of reactor-grade plutonium that would have increased the average percentage. It is assumed also that approximately two times as much plutonium-239 fissions as is converted into plutonium-240. In the Hanford reactors and the NRX heavy-water reactor the ratios of the neutron cross-sections for plutonium-239 fission and plutonium-239 $\rightarrow$ plutonium-240 are 2.1 and 2.2 respectively, Alexander Glaser, *op. cit.*, Table III.

26. T. B. Cochran et al*., op. cit*., p. 185.

27. Alexander Glaser, *op. cit.*

28. *ibid*.

29. At 950 tons of natural uranium per ton of weapon-grade plutonium produced, there would have been 52,000 tons of reprocessed natural uranium from Hanford and 17,000 tons from Savannah River associated with the production of weapon-grade plutonium and 6,000 tons associated with the production of the 9 tons of fuel-grade plutonium that were separated. These numbers would have to be reduced by the 2,159 tons of reprocessed uranium at Fernald and 1590 tons left at Hanford (see above). Reportedly, however, 86,584 metric tons of reprocessed uranium with an enrichment of 0.64 percent and 3,285 tons of reprocessed uranium from Savannah River with an enrichment of 0.59 percent were re-enriched to 0.73 percent, R. F. Smith, U.S. DOE, Historical Impact of Reactor Tails on the Paducah Cascade," March 1984, (cited in Peter Diehl, "Composition of the U.S. DOE Depleted Uranium Inventory" (undated) <http://www.wise-uranium.org/pdf/duinve.pdf≥, Table 2). The amount of enrichment work and depleted uranium would be increased slightly if one took into account the fact that uranium-236 would have accumulated in the recycled uranium and required additional enrichment to offset its poisoning effect.

30. Thomas B. Cochran, William M. Arkin, Robert S. Norris, and Milton M. Hoenig. *Nuclear Weapons Databook. Vol. 3., U.S. Nuclear Warhead Facility Profiles* (Cambridge, MA: Ballinger, 1987), pp. 22–23.

31. Note, however, that the average amount of plutonium reported in the unreprocessed Hanford fuel is 1.9 grams/kgU, U. S. Department of Energy, Fluor Hanford, "Nuclear Material Mass Flow and Accountability on the Hanford Site," HNF-8069 (August 2001), Table 8.