

# APPENDIX

## How Much Pu-240 Has the U.S. Used in Nuclear Weapons: A History

### *Introduction and Summary*

Ideally plutonium used in nuclear weapons would contain only the isotope Pu-239. However, the United States discovered in 1944 that plutonium produced in nuclear reactors must contain at least a small percentage of the isotope Pu-240. The relatively high spontaneous fission rate of Pu-240 causes this isotope to release neutrons which can cause unboosted nuclear weapons to have a significant probability of predetonating, i.e. starting the nuclear reaction prematurely, resulting in a lower than designed nuclear yield. Therefore, limits were placed on the percentage of Pu-240 in the plutonium used in early U.S. nuclear weapons so as to ensure a reasonable probability of achieving the design yield. Plutonium that the United States uses in its nuclear weapons is termed “weapon-grade.”

As is discussed in chapter three, currently the United States defines weapon-grade plutonium as having a Pu-240 content of less than 7% and U.S. nuclear weapons use plutonium with a Pu-240 content of about 6%. Given that all U.S. nuclear weapons are now boosted, this limit on Pu-240 content has nothing to do with the probability of predetonation, but rather with other properties of the plutonium, such as radiation output. But this was not always the case. The

United States did not deploy boosted fission weapons until 1957 and continued to stockpile unboosted nuclear weapons well into the 1960s.<sup>197</sup>

The declassification of documents related to the operation of the plutonium production reactors at Hanford allows the construction of an approximate history of the Pu-240 content of U.S. weapon-grade plutonium. In the 1940s the limit on the permissible Pu-240 content was fairly low due to the relatively slow assembly time associated with early implosion fission weapons. As implosion technology improved, the Pu-240 limit increased.

The Nagasaki weapon used plutonium that was only 1.0% Pu-240.<sup>198</sup> Soon after the Nagasaki weapon was employed, the limit was increased to 2.0% Pu-240. In 1949 the limit was increased to 3.8% and in March 1951 to 5.5%. This high limit is an indication that, even in 1951, unboosted implosion fission technology had been significantly improved over that used in the Nagasaki weapon. Indeed in the 1950s, U.S. implosion fission weapons employed a technique known as levitation, which is the use of an air gap between the weapon's fissile core and the tamper. This air space allows the implosion wave to increase in speed and compress the nuclear core more rapidly.

In 1954, the Pu-240 limit for much of the weapon-grade plutonium being produced was 8.8%. However, Hanford never produced weapon-grade plutonium with a Pu-240 percentage this high since operating problems at Hanford, not the neutron output of the pluto-

---

197. N. Stetson et al., *Savannah River Production Reactor History*, CIV-685-2A, September 1963.

198. Gregory S. Jones, "Fissile Material Conversion Times, Wastage and Significant Quantities: Lesson from the Manhattan Project," December 16, 2015, p. 10, available from <http://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1>.

nium, determined the Pu-240 content of the plutonium. Due to the fuel rupture problem, Hanford was only able to produce plutonium that was 7.5% Pu-240 in 1955. This was lowered to 6.8% in 1956 and in 1957 and 1958 further lowered to 4.7% Pu-240.

At about the same time (1954-1956), Hanford had a program to produce low burnup plutonium with a Pu-240 content of 2.0% which was later raised to 2.5%. This involved the C reactor and part of the capacity of the other reactors. About half the plutonium produced at Hanford during these years was low burnup. Presumably this low Pu-240 plutonium was intended for the primaries of the unboosted thermonuclear weapons in use at this time.

With the advent of tubular fuel elements in 1959, the limit was increased to 6.0%, and it soon became frozen at this level. It is interesting to speculate what might have been the result if Hanford had been able to produce plutonium that was 8.8% Pu-240 in the mid-1950s. Perhaps this Pu-240 percentage would have become the standard and all U.S. weapon-grade plutonium today would have a Pu-240 content of 8.8%.<sup>199</sup> Table 12 gives a breakdown of my estimates of the amounts of weapon-grade plutonium produced at Hanford with various Pu-240 contents and the dates and reactors involved in its production.

---

199. Note that the U.S.-Russian 2000 Plutonium Management and Disposition Agreement defines weapon-grade plutonium as having no more than about 9.1% Pu-240 (a Pu-240 to Pu-239 ratio of no more than 0.1).

Pu-240 Content*	Amount in Metric Tons	Dates Produced and Reactors Used
2.0%	1.6	1945-1948, B, D & F 1954, C & part of the capacity of other reactors
2.5%	1.9	1955-1956, C & part of the of capacity of other reactors
3.8%	0.7	1949-1951 B, D, DR, F & H
4.7%	6.4	1957-1958 All reactors except N
5.5%	2.8	1951-1954 B, D, DR, F, H & C except not C in 1954
6.0%	39.0	1959-1971 & 1983- 1987 All reactors
6.8%	1.2	1956 Part of the ca- pacity B, D, DR, F, H, KE & KW
7.5%	0.9	1955 Part of the ca- pacity B, D, DR, F, H, KE & KW
5.6% Weighted Average	54.5 Total	

**TABLE 12: Amounts of Weapon-Grade Plutonium Produced at Hanford: Pu-240 Content, Dates Produced & Reactors Used.**

\*Before 1961 the Pu-240 content varied significantly from batch to batch.

*History of the Production of Weapon-Grade Plutonium at Hanford*

The declassification of many documents regarding the plutonium production operations at Hanford provides much information but using these documents also presents some difficulties. Only some of the documents produced by Hanford have been declassified, so it is sometimes difficult to place a document in the proper context. Also, the documents use a good deal of jargon (such as “E-metal,” i.e. uranium fuel enriched to 0.95%) whose meaning was obvious at the time but not so today.

The meaning of some technical terms is not always clear. An important term for this work is MWD/ton (megawatt-days per ton), which is the measure of fuel burnup. For a number of decades it has been standard to measure burnup in terms of MWD/Te, where the “Te” is a metric ton (2,205 lb). In most of the Hanford documents, it is not obvious what kind of ton is meant. It would be tempting to assume that they meant metric tons but, in fact, they are short tons (2,000 lb.).

Finally, due to the limitations of the time, some of the information was simply incorrect. Of great importance for this work is Hanford’s estimate of the Pu-240 content of the plutonium it was producing. But in the 1950s Hanford was not measuring this directly but rather measuring the property that was actually important for weapons use, namely the plutonium’s neutron production in units of n/g-s (neutron per gram-seconds). Hanford then converted this neutron measurement into a Pu-240 content by using the neutron production rate of Pu-240. But Hanford’s estimate of the Pu-240 neutron production rate in the 1950s was too high by about 30 percent, which meant that its estimate of the Pu-240 content of any given plutonium was about 30 percent too low.<sup>200</sup>

---

200. Compare Figure 13 (p. 42) from F. E. Kruesi, J. O. Erkman, and D. D. Lanning, “Critical Mass Studies of Plutonium Solutions,” General Electric,

Table 13 shows the operating history of the Hanford plutonium production reactors. The B, D, and F reactors were built during World War II. Soon after the war, it was discovered that the operation of the reactors was causing their graphite moderator to expand to such an extent that it threatened the continued operation of the reactors. The B reactor was shut down to preserve some of its operating life and the H reactor started construction. The situation at the D reactor was so serious that the DR reactor was built to replace it. However, a solution was found to the graphite problem and the D reactor was never shut down.<sup>201</sup>

These first five reactors (B, D, F, H, & DR) had an identical design. The C reactor was a slightly improved design. The KW and KE reactors were improved designs with a significantly higher power level and conversion ratio. The N reactor used enriched uranium fuel and was designed to produce electricity as well as plutonium. Most of the plutonium produced by this reactor was not weapon-grade due to the higher burnup of its enriched uranium fuel.

To a first approximation the amount of plutonium produced is directly proportional to the power level of a reactor. As can be seen from Table 13, the power level of the earliest reactors was increased by nearly a factor of ten over their operating life. This was achieved in steps over time by allowing higher water discharge temperatures, increasing reactor cooling capacity, and providing small amounts of enriched uranium. The reactors at Hanford produced a total of about 54.5 metric tons of weapon-grade plutonium.<sup>202</sup> The annual produc-

---

Richland Washington, May 19, 1952, HW-24514 with the more accurate Figure 6 (p.32) "Hanford Reactor and Separations Facility Advantages," Hanford Atomic Products Operation, Richland Washington, June 27, 1963, HW-78100.

201. It was found that heating the graphite annealed the damage caused by irradiation.

202. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from <https://www.osti.gov/opennet/servlets/>

tion peaked at over 4 metric tons between 1960 and 1965 and was essentially over by 1971.<sup>203</sup>

As was discussed above, the plutonium in the Nagasaki weapon had a Pu-240 content of 1.0%. But even before the Nagasaki weapon had been used in combat, General Groves, the head of the Manhattan Project, reported that the Pu-240 content of the plutonium was going to be increased.<sup>204</sup> In August, “the customer” requested that the reactor fuel burnup be limited to 200 MWD/ton, which would result in a Pu-240 content of about 2.0%.<sup>205</sup> An operating report from November 1945 refers to 200 MWD/ton as “normal discharge material.”<sup>206</sup> Apparently this fuel burnup goal lasted until about the end of 1948. Between 1944 and the end of 1948, Hanford produced about 800 kilograms of plutonium.<sup>207</sup>

---

[purl/219368/219368.pdf](https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf).

203. The N reactor produced 2,778 kilograms of weapon-grade plutonium between 1983 and 1987. Ibid.

204. General Leslie Groves, “Memorandum to the Chief of Staff,” July 30, 1945, Manhattan Engineering District Papers, Box 3, Folder 5B, Record Group 77, Modern Military Records, National Archives, Washington, D.C.

205. W.O. Simon, “Hanford Engineer Works monthly report, August 1945,” September 9, 1945 HW-7-2361-Del.

206. W.E. Jordan “100 Area Technical Activities Report-Physics, 10/25/45 to 11/25/45,” November 29, 1945, E.I. Du Pont De Nemours & Company.

207. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from <https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf>.

Reactor	Operating Dates	Design Power Level MWt	Highest Sustained Power Level MWt
B	9/44-3/46 7/48-2/68	250	2210
D	12/44-6/67	250	2165
F	2/45-6/65	250	2040
H	10/49-4/65	400	2140
DR	10/50-12/64	250	2015
C	11/52-4/69	650	2500
KW	1/55-2/70	1850	4400
KE	4/55-1/71	1850	4400
N	12/63-1/87	4000	4000

**TABLE 13: Operating History of the Hanford Plutonium Production Reactors**

At the beginning of 1949, the fuel burnup discharge goal was raised to 400 MWD/ton, which is a Pu-240 content of about 3.8%. During the first half of 1949, the fuel burnup was gradually raised from 200 MWD/ton to 400 MWD/ton.<sup>208</sup> It continued at this level until March 1951. During this time, Hanford produced about 700 kilograms of plutonium.<sup>209</sup>

In March 1951, the burnup goal was raised to 600 MWD/ton which yields a Pu-240 content of about 5.5%.<sup>210</sup> Apparently, the burnup

---

208. Various P Division monthly reports.

209. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from <https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf>.

210. DL Deneal, "Historical Events-Single Pass Reactors and Fuels Fabrication," April 10, 1970, DUN-6888, p. 7.

was raised to this new level almost immediately. Unfortunately, this burnup increase led to an immediate increase in the number of fuel ruptures.

Fuel ruptures were a major concern for the operations at Hanford. When a fuel element ruptured, the hot metallic uranium was exposed to the water coolant. It would oxidize and expand blocking, the fuel channel. This would cut off the flow of coolant to the other fuel elements and in the worst case, these fuel elements could catch fire and set the entire reactor ablaze. Therefore, there were systems that quickly detected any fuel rupture. Once detected, the reactor would be shut down and the ruptured element removed.

In the best case, the ruptured element could be removed in just a half an hour. In the worst case, the fuel element would be stuck and so much force would be required to remove it that the aluminum fuel channel would be damaged and would have to be replaced. Or the swollen ruptured fuel element could rupture the fuel channel, leading large amounts of water to spill into the reactor. The reactor's graphite would then need to be dried before the reactor could be restarted. In either case, days of reactor operation could be lost to a fuel rupture. In optimizing the plutonium production operations at Hanford, the likelihood of fuel ruptures needed to be taken into account. Since this likelihood increased with fuel burnup as well as reactor power level, the threat of fuel rupture tended to limit the fuel burnup and thereby the Pu-240 content of the plutonium produced. By improving fuel quality, it was possible to reduce the fuel rupture rate and maintain the 600 MWD/ton goal at the five oldest reactors (the B, D, F, H, and DR) through the end of 1954.

In 1954, the new C reactor was tasked to produce low burnup plutonium. In that year it produced fuel with a burnup of about 200 MWD/ton which would be a Pu-240 content of about 2.0%. Additional reactors apparently operated with dual burnup goals and also produced this low burnup plutonium in addition to high burnup plu-

tonium. In 1955, the low burnup goal was raised to 250 MWD/ton, which is a Pu-240 content of about 2.5%. This program continued until about the end of 1956. It is unclear which of the various other reactors produced low burnup plutonium or how much each reactor produced. However, reporting from January through August 1955 indicated that about half of Hanford's plutonium production was low burnup material.<sup>211</sup> I assume that this was the case for the entire 1954-1956 period. The production of 2.0% Pu-240 plutonium in 1954 would have been about 800 kilograms. The production of 2.5% Pu-240 plutonium in 1955 and 1956 was about 1,900 kilograms. Presumably this low Pu-240 plutonium was intended for the primaries of the unboosted thermonuclear weapons in use at this time.

A 1954 document reveals the specific maximum plutonium neutron output in terms of n/g-s values that were required by the U.S. Atomic Energy Commission.<sup>212</sup> For the low burnup plutonium, its n/g-s should not exceed 20, which would be a Pu 240 content of about 2.2%. For all other weapon-grade plutonium its n/g-s should not exceed 80 which would be a Pu-240 content of about 8.8% (a burnup of about 1,050 MWD/ton).

In 1955, Hanford tried to move towards the high burnup plutonium goal by increasing the burnup to 900 MWD/ton (7.5% Pu-240), but fuel ruptures became a problem.<sup>213</sup> In 1956 Hanford lowered the goal to 800 MWD/ton (6.8% Pu-240) but the fuel rupture problem continued. I estimate that Hanford produced about 900 kilograms of high burnup plutonium in 1955 and about 1,200 kilograms in 1956. In the mid-1950s, it was the fuel rupture rate, not the plutonium

---

211. K. F. Paulovich, "Monthly Reports, January-December 1955, Reactor Operation Branch, HAN-58378, September 1, 1955.

212. R. O. Gumprecht, "Plutonium Product Quality," May 28, 1954, HW-31952, General Electric, Richland Washington.

213. "1955 at Hanford," HW-39900, General Electric, Richland, Washington.

neutron output that determined the Pu-240 content of the plutonium produced.<sup>214</sup>

As the power levels of the reactors continued to increase, the fuel ruptures increased as well. As a result, in 1957 and 1958 the fuel burnup was reduced to 500 MWD/ton (a Pu-240 content of about 4.7%). Hanford produced about 6,400 kilograms of plutonium during these two years.<sup>215</sup> Yet it appears that through 1958 the high 8.8% Pu-240 limit remained in effect and Hanford planned to adopt the goal of 800 MWD/ton (6.8% Pu-240) when better fuel became available.<sup>216</sup>

However, in 1959 just as the less rupture prone tubular fuel elements (I & E fuel elements in Hanford jargon) became available, the Pu-240 limit was set at 6.0%, which limited fuel burnup to just 675 MWD/ton. In early 1961, Hanford was given an explicit Pu-240 goal of 6.0%, instead of the goal being set in terms of fuel burnup. Further, this new goal had to apply to all the plutonium produced, whereas in the past there had been significant variation in the Pu-240 content from batch to batch as Hanford optimized the reactor operations to maximize plutonium output. This new goal caused Hanford some concern since it would be difficult to convert this requirement into a fuel burnup (it was difficult to keep track of the fuel burnup in each fuel channel).<sup>217</sup> In the end, it appears that Hanford had no trouble meeting this goal.

---

214. R. A. Pugh, "Final Report-Production Test 200-2 Processing of Special Irradiated Plutonium," September 27, 1956, HW-45940, p. 4.

215. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from <https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf>.

216. Hanford Atomic Products Operation, "Five-Year Program," HW-55767, General Electric, Richland, Washington, May 19, 1958.

217. See, L. W. Lang & W. I. Neef, "Notes on Reactor Operation within a Prod-

There is no indication that there were any further changes to the Pu-240 requirement for weapon-grade plutonium. By the mid-1960s the plutonium production declined as various reactors were shut down and some plutonium was produced for non-weapon purposes. Weapon-grade plutonium production at Hanford ended in 1971 with the shutdown of the KE reactor.

The N reactor continued in operation until 1987. However, most of the plutonium this reactor produced was for non-weapon purposes though it did produce 2,778 kilograms of weapon-grade plutonium between 1983 and 1987.<sup>218</sup> From 1959 through 1987, when the Pu-240 specification was 6.0%, Hanford produced 39,000 kilograms of plutonium.<sup>219</sup> This was about 72% of Hanford's total weapon-grade plutonium production.

Much less is known about the plutonium production at Savannah River since far less has been declassified about the reactor operations there. However, of the 36.1 metric tons of weapon-grade plutonium produced there, 32.5 metric tons (90 percent of the total) were produced after 1958. Therefore, it is safe to say that the vast majority of the weapon-grade plutonium produced at Savannah River had a Pu-240 content of 6.0%.<sup>220</sup>

---

uct Specification," June 9, 1961, HW-69904 and T. Prudich, "Product Quality and an Interim Goal Exposure Plan," June 12, 1961, HW-69912.

218. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from <https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf>.

219. *Ibid.*

220. Between 1981 and 1990, Savannah River produced plutonium with a Pu-240 content of 3%. This material was blended with fuel-grade plutonium to produce weapon-grade plutonium. See *Ibid.*, pp. 30-31.

Table 12 gives a breakdown of the amounts of weapon-grade plutonium produced at Hanford with various Pu-240 contents. The Nagasaki weapon used plutonium that was only 1.0% Pu-240. Soon after the Nagasaki weapon was employed, the limit was increased to 2.0% Pu-240. In 1949, the limit was increased to 3.8% and in March 1951 to 5.5%. This high limit is an indication of the rapid improvement of unboosted implosion fission weapon technology in the U.S. arsenal. New nuclear weapon states today would likely develop weapons similar to U.S. 1951 technology. Indeed, even more than 50 years ago, both France's and China's first nuclear test devices were clearly much superior to the U.S. Nagasaki design.

Until 1951 the Pu-240 content was determined by the specifications for plutonium neutron output. Between 1951 and 1959, it appears that fuel ruptures, not plutonium neutron output, determined the Pu-240 content of the plutonium.

Though at one time plutonium with a Pu-240 content of 8.8% was acceptable from a neutron output standpoint, Hanford could not efficiently produce such plutonium. If Hanford had been able to produce large amounts of plutonium that was 8.8% Pu-240, such plutonium might have become the standard and all U.S. weapon-grade plutonium today might have an 8.8% Pu-240 content. It is interesting to note that the U.S.-Russian 2000 Plutonium Management and Disposition Agreement defines weapon-grade plutonium as having a Pu 240 content of no more than about 9.1% (a Pu-240 to Pu-239 ratio of no more than 0.1).