Military Fissile Material Production and Stocks in France

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Abstract

France ended fissile material production for military purposes in the 1990s and has started to decommission and dismantle its production facilities at Marcoule and Pierrelatte. This paper provides an overview of the French production complex and presents new estimates of historic fissile-material production, which include neutronics calculations for the production reactors at Marcoule. The analysis suggests that France's military inventories of plutonium and highly enriched uranium significantly exceed the requirements for its current nuclear arsenal. France has made public details about the total number of its nuclear weapons, but has so far been reluctant to make a similar declaration about its military fissile-material stockpiles. This paper proposes a series of steps that France could take towards greater transparency that take advantage of the dismantlement activities at Marcoule and Pierrelatte to demonstrate new verification technologies and approaches and that would facilitate progress towards nuclear disarmament.

Background[1]

French nuclear development started during World War II with the U.S. Manhattan project, in which a number of French scientists participated. Immediately after the war, France established its Atomic Energy Commission (*Commissariat à l'Energie Atomique,* CEA) and began exploring the possibility of developing its own nuclear weapons program in the early 1950s. Most significantly, the CEA secretly established a Nuclear Explosives Committee (*Comité des Explosifs Nucléaires,* CEN) in November 1954, which immediately devised plans for acquiring source materials, namely uranium and heavy water, and constructing the first plutonium production reactors at Marcoule. In effect, the French nuclear establishment pursued a nuclear weapons options before a clear political decision had been taken to acquire or even seriously consider them. In particular, France started production of weapon-grade plutonium in mid-1955, ostensibly for peaceful purposes,[2] and yet it was only after the Suez Crisis in late 1956 that the French government formulated a more explicit but still ambiguous position towards nuclear weapons.[3] Only when General Charles De Gaulle returned to power in June 1958, first as Prime Minister and then as President, was the weapons program fully endorsed politically. Given the extensive preparations, it then proceeded rapidly: Only twenty months later, on 13 February 1960, France detonated its first nuclear weapon in the French-Algerian Sahara desert.

As a consequence of the CEA's organizational setup, France did not develop separate civilian and military facilities and fuel cycles. Estimating France's stockpile of military fissile materials therefore remains difficult—even today. Based on the data available, we estimate France's stockpile of military plutonium to be on the order of 6 ± 1 tons. The current HEU inventory is estimated to be 26 ± 6 tons of unirradiated weapon-grade-equivalent material; the HEU estimate is more uncertain because of a lack of public information about the capacity of the Pierrelatte enrichment plant.

Highly Enriched Uranium

France announced the definitive halt of fissile material production for weapons purposes on 22 February 1996 and, by the end of June 1996, the gaseous diffusion enrichment plant at Pierrelatte stopped producing highly enriched uranium (HEU).

France has produced its stockpile of HEU at a dedicated enrichment complex near Pierrelatte at the Tricastin site (Figure 1). Construction of the Pierrelatte enrichment plant began in 1960 and consisted of four different buildings or units of decreasing size and capacity: the "low plant" (*usine basse,* UB) enriched up to 2%, the "middle plant" (*usine moyenne,* UM) up to 7%, the "high plant" (*usine haute,* UH) up to 25%, and the "very-high plant" (*usine très haute,* UTH) to 90% and higher, reportedly to 95%.[4]

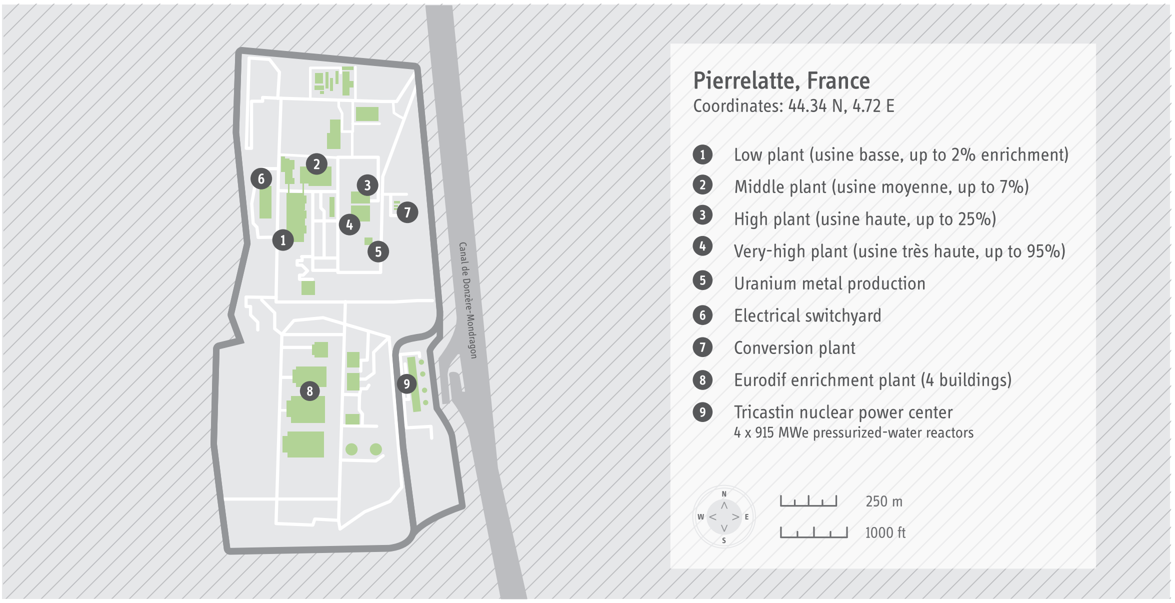


Figure 1: Pierrelatte gaseous diffusion enrichment plant. Between 1967 and 1996, France produced an estimated 35 ± 5 tons of highly enriched uranium for weapons and naval fuel at the Pierrelatte plant. France, unlike the United States and the United Kingdom, has not declared its HEU production.

The first unit to come online was the low plant in 1964, and production of highly enriched uranium using all four units started in early 1967. The total capacity of the plant has not been made public.

There is very little information available about the original capacity of the plant. In 1956, French officials set the military requirements of the weapons program at "a minimum of 600–700 kg of weapon-grade HEU per year,"[5] which would correspond to an enrichment capacity of 120,000–200,000 SWU/yr. One 1996 publication authored by CEA officials quotes the capacity as "several 100,000 SWU per year."[6] One can also use the available supply of uranium-hexafluoride for an upper estimate of the plant capacity: The dedicated conversion plant at Pierrelatte (SUCP, *Société des Usines Chimiques de Pierrelatte,* now Comurhex) was designed to produce 500 tons of uranium in uranium-hexafluoride (UF_6) per year.[7] For typical depletion levels of 0.3–0.4%, this feedstock would be sufficient to support a plant producing weapon-grade uranium with a capacity of 300,000–450,000 SWU per year.

The stockpile estimate below assumes a value of 300,000 SWU per year as the average lifetime capacity of the Pierrelatte plant. At this capacity, the plant would have produced a total of 9 million SWU in its almost thirty years of operation, i.e., from early 1967 through mid-1996.

The Pierrelatte enrichment complex is separate from a second enrichment plant, the Eurodif plant, on the same site. Construction of the Eurodif plant started much later, in 1976, and its first production of LEU began in 1979. In 1982, the plant reached enrichment levels of 3.5% and its nominal capacity of 10.8 million SWU per year.[8] The Eurodif and Pierrelatte plants were not operated independently, however. Between 1979 and 1982, product from the Eurodif plant was transferred to the low and middle plants of Pierrelatte for further enrichment. In 1982, when the Eurodif plant finally achieved the capability to enrich uranium to 3.5%, the low and middle plants at Pierrelatte were shut down. Thereafter, production of HEU at Pierrelatte used pre-enriched material that it received from the Eurodif plant.

The Pierrelatte plant was also used for the production of low-enriched uranium for civilian use and for naval fuel, in particular before Eurodif became fully operational in 1982. Albright, Walker, and Berkhout offer a detailed discussion estimating the total enrichment work that was dedicated for these purposes.[9] They assign about one million SWU for civilian LEU and one million SWU for naval-core production, some of which used highly enriched fuel. Using these values, and based on the reference value of 9 million SWU for the cumulative enrichment work delivered by the plant, leaves 7 million SWU available for HEU production, which corresponds to about 35 ± 5 tons of weapon-grade HEU.

The main removals from this HEU stockpile were due to the operation of the two HEU-fueled *Célestin* tritium-production reactors, which were also used for plutonium and special-isotope production, and are discussed in more detail below. Each reactor was rated at 190 MW thermal and may have required about 145 kg of HEU fuel per year at a capacity factor of 75%. For about 20 years, both reactors operated simultaneously (1970–1990), while only one reactor was operating at a time between 1991 and final shutdown in 2009. Overall, this operational history corresponds to about 60 reactor years, requiring about 8.7 tons of HEU. Allowing for additional temporary outages, and the possibility of using recycled HEU fuel, lifetime HEU demand of the *Célestin* reactors could be on the order of 5–7 tons.

Nuclear weapon tests constitute the second major category of HEU removals. France conducted a total of 210 tests, which would have consumed 2–4 tons of HEU, assuming that the test devices contained 10–20 kg of HEU on average. France ended its nuclear testing program in January 1996, signed the Comprehensive Test Ban Treaty, and shutdown its test site in the South Pacific. With the shutdown of the *Célestin* reactors in December 2009, France should no longer be consuming HEU on a large scale. Accordingly, it is estimated that France's remaining stock of (unirradiated) HEU should be on the order of 26 ± 6 tons today.

Military Plutonium

Large-scale plutonium production for military purposes in France started in 1956 and ceased in 1992. To support its weapons program, France built a series of dedicated production reactors at its Marcoule Site (Figure 2), but also used several civilian reactors owned and operated by *Electricité de France* (EDF) to produce additional weapon-grade plutonium and tritium. With the exception of the fast-neutron reactor *Phénix* and the two *Célestin* heavy-water reactors, both located at Marcoule and discussed further below, all other reactors were graphite-moderated and gas-cooled (*Uranium Naturel Graphite Gaz,* UNGG) and are being decommissioned.

G1, G2, and G3 reactors. The first dedicated production reactor at Marcoule (G1) was air-cooled and had a thermal power of 46 MW. Routine production of weapon-grade plutonium began in 1956 and ended in 1968. According to the 1962 CEA Annual Report, G1 had produced a total of 59.6 GW-days of fission heat by the end of 1962, including 12.4 GW-days produced in that year. Assuming the same annual output between 1963 and 1968, the energy generated in G1 during its lifetime would be on the order of 134 GW-days. Using an effective production rate of 0.95 grams of plutonium per MW-day, the cumulative plutonium production in G1 is estimated to be 125–130 kg.

The most important plutonium-production facilities in the French nuclear weapons complex were the follow-on reactors G2 and G3, which came online in 1958 and 1959. These two identical reactors were carbon-dioxide-cooled and reportedly achieved a power level of about 250 MW thermal each, or possibly more as discussed below. For extended periods of time, these reactors also produced electricity.

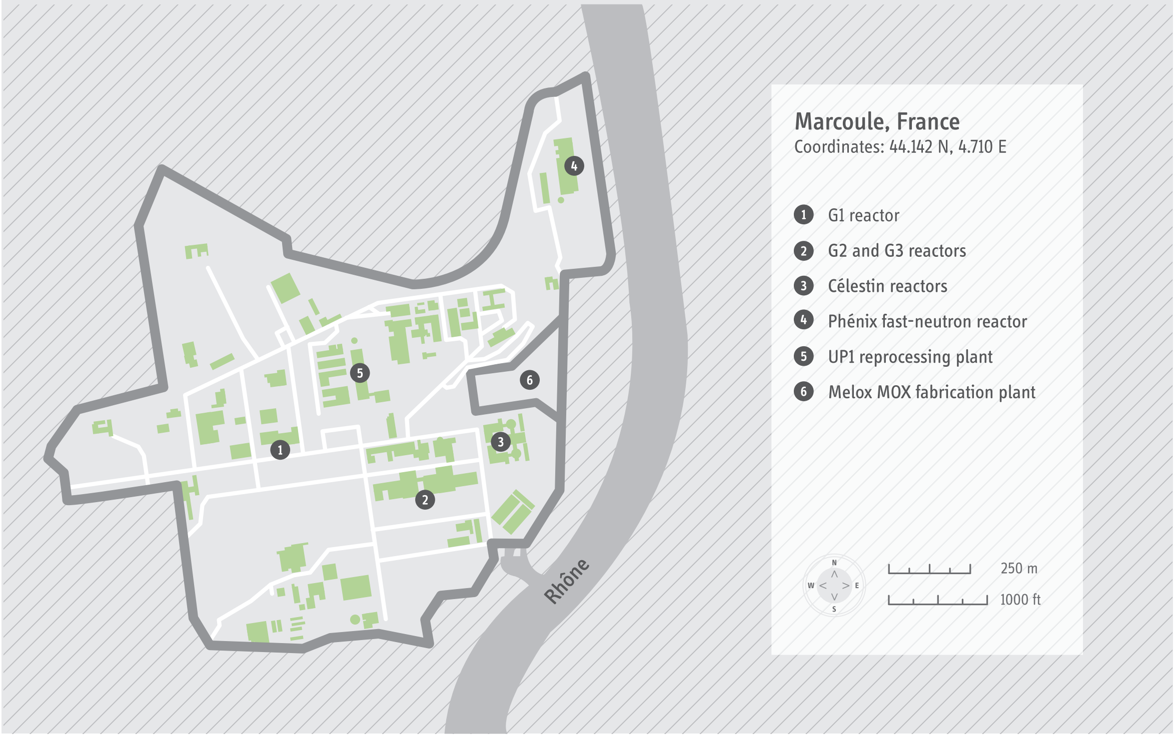
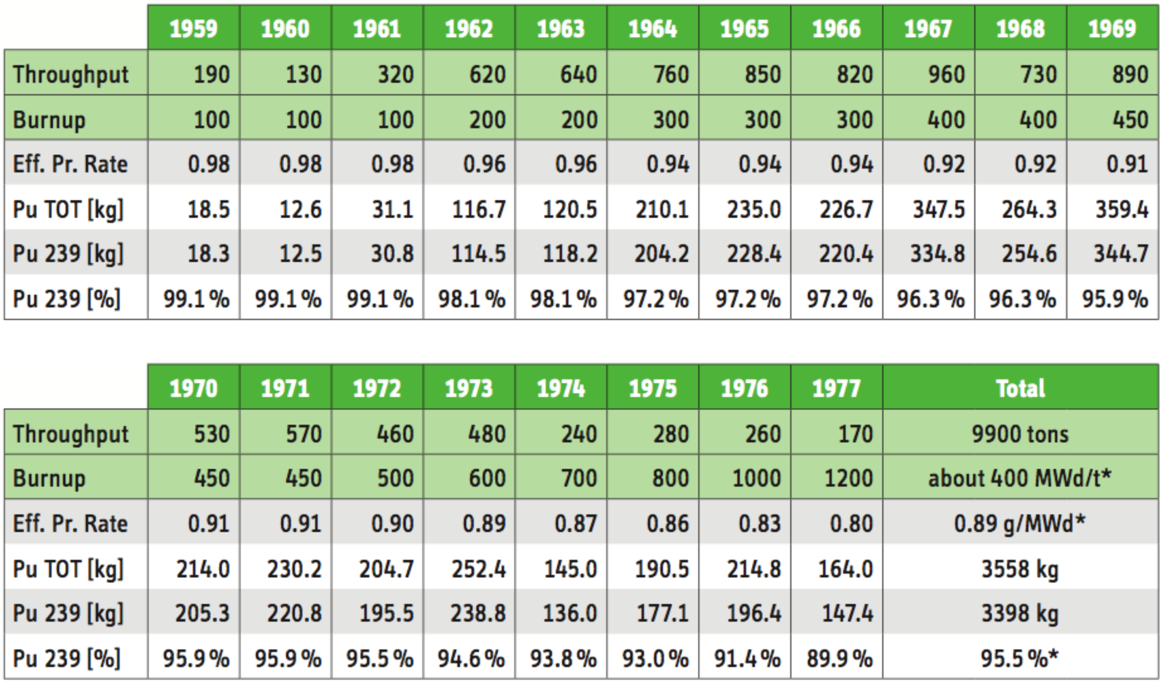


Figure 2: The Marcoule Site near Avignon in the South of France. In addition to the military reprocessing plant UP1, the site hosted several reactors that were used for dedicated plutonium (G1, G2, G3, and *Phénix*) and tritium production (two *Célestin* reactors, which also were used for plutonium and special-isotope production). With the shutdown of both *Célestin* reactors in December 2009, no operational production reactors remain at Marcoule. Map adapted from CEA drawing.

In 1980, the National Atomic Energy Trade Union (SNPEA) of the French Democratic Confederation of Labor (CFDT) published a 500-page account of the French nuclear program: *Le dossier électronucléaire.*[10] The information included annual throughput and average fuel burnup for the production reactors G1, G2, and G3 through 1977. Combined with neutronics calculations performed for this analysis, the data can be used to calculate annual plutonium production and the isotopics of the material produced in those years (Table 1). The results indicate that these three reactors produced a combined total of 3.56 tons of weapons plutonium by 1977. This value is surprisingly high and implies that G2 and G3 were operated at 300–350 MW throughout the 1970s. Such a power level has not been confirmed by other sources, which quote a maximum of 260 MW, but the information published by SNPEA/CFDT appears credible and is used for the stockpile estimate below.

According to the data published in the *dossier électronucléaire,* the average burnup of the fuel discharged from G2 and G3 increased continuously over time. After 1975, it had reached 1000 MWd/t, which—if correct—implies that these reactors were no longer producing weapon-grade material. It is possible that, by then, the mission of the reactors had shifted, to the production of startup fuel for the *Célestin* and *Phénix* reactors. Alternatively, newly produced non-weapon-grade plutonium could have been used for blending with super-grade plutonium produced until the mid-1960s.



	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	Total
Throughput	190	130	320	620	640	760	850	820	960	730	890	530	570	460	480	240	280	260	170	9900 tons
Burnup	100	100	100	200	200	300	300	300	400	400	450	450	450	500	600	700	800	1000	1200	about 400 MWd/t*
Eff. Pr. Rate	0.98	0.98	0.98	0.96	0.96	0.94	0.94	0.94	0.92	0.92	0.91	0.91	0.91	0.90	0.89	0.87	0.86	0.83	0.80	0.89 g/MWd*
Pu TOT [kg]	18.5	12.6	31.1	116.7	120.5	210.1	235.0	226.7	347.5	264.3	359.4	214.0	230.2	204.7	252.4	145.0	190.5	214.8	164.0	3558 kg
Pu 239 [kg]	18.3	12.5	30.8	114.5	118.2	204.2	228.4	220.4	334.8	254.6	344.7	205.3	220.8	195.5	238.8	136.0	177.1	196.4	147.4	3398 kg
Pu 239 [%]	99.1 %	99.1 %	99.1 %	98.1 %	98.1 %	97.2 %	97.2 %	97.2 %	96.3 %	96.3 %	95.9 %	95.9 %	95.9 %	95.5 %	94.6 %	93.8 %	93.0 %	91.4 %	89.9 %	95.5 %*

Table 1: Estimated annual plutonium production in G1, G2, and G3, 1959–1977, based on information published in the *dossier électronucléaire.* Throughput is given in metric tons of heavy metal, burnup in MW-days/ton, and effective production rate in g/MW-day. Asterisks indicate weighted averages.

To estimate post-1977 plutonium production in G2 and G3, we assume 70,000 MWd/yr per reactor and a plutonium production rate of 0.8 g/MWd, which corresponds to burnup levels on the order of 1000 MWd/t. Together, G2 and G3 may have developed an additional 595 GW-days in 2 and 6 1/2 years, respectively, and produced about 0.4–0.5 tons of plutonium between 1978 and final shutdown.

In total, we estimate that G1, G2, and G3 produced about 4 tons of weapons plutonium with an average plutonium-239 content of about 94.9%. This estimate is significantly higher than previous estimates by Albright, Walker, and Berkhout (2.9 ± 0.2 tons) or historic estimates by the U.S. Central Intelligence Agency ("over 2.5 tons").[11] If sub-weapon-grade plutonium produced after 1975 was not added to the stockpile of weapons plutonium, and served a different purpose, then the total production of weapon-grade plutonium in the G-reactors would be about 3.2 tons instead (96% Pu-239). The CIA estimate however confirms the total throughput of about 10,000 tons of uranium.

Phénix. The Marcoule site also hosted the fast-neutron reactor *Phénix*, which went critical in mid-1973 and, until the late 1990s, operated at a power level of 250 MWe (563 MWt). It is widely believed that plutonium from this reactor has contributed to the French military stockpile of fissile material.

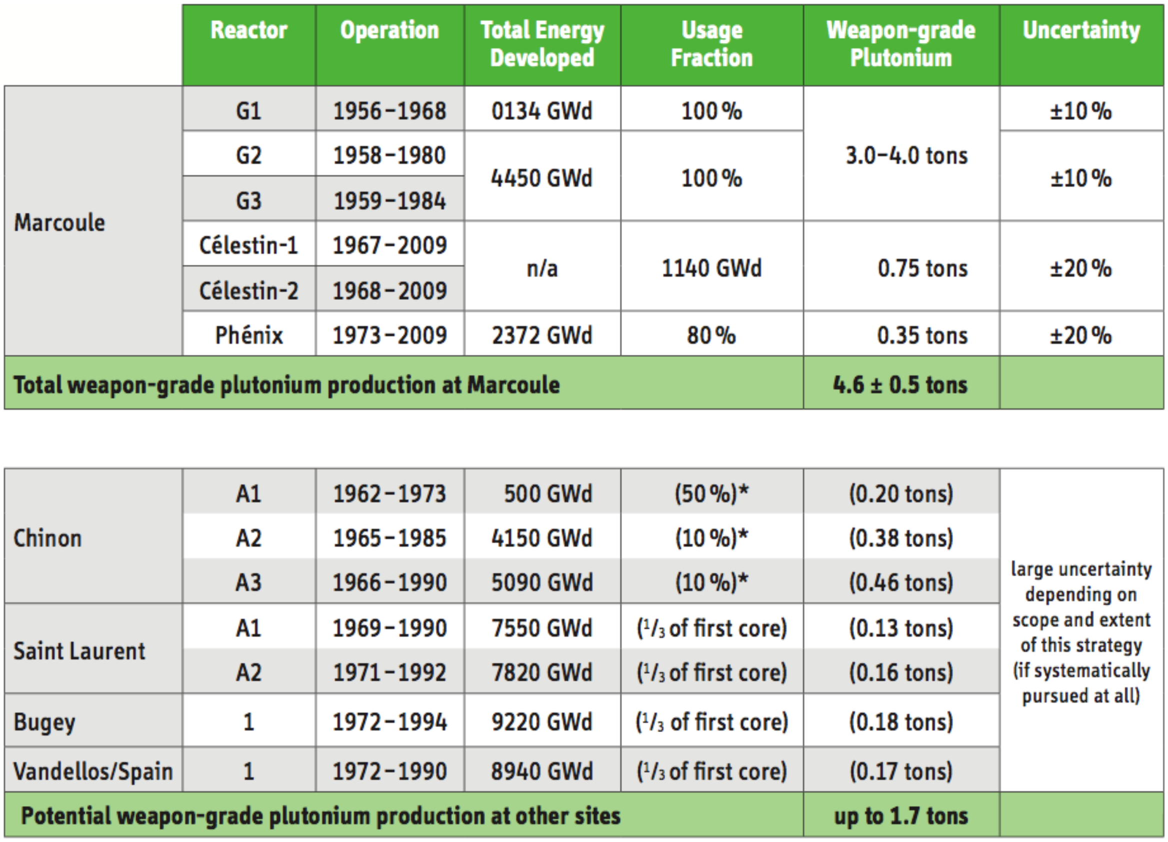
Phénix achieved capacity factors of almost 60% in the late 1980s before it began experiencing more serious operational problems. Throughout the 1990s, the reactor was mostly shut down. We therefore assume that its military mission ended in 1990. The reactor restarted operation in 2003 at a reduced power level before its final shutdown in September 2009. To estimate the contribution of *Phénix* to the French stockpile of weapons plutonium, it is assumed that only the surplus plutonium—not the total amount of weapon-grade plutonium—extracted from the blankets was transferred to the weapons program. The surplus fissile plutonium M_Δ produced in a breeder reactor can be calculated from the definition of breeding ratio $BR = 1 + M_\Delta/M_C$, where M_C is the total amount of fissile material consumed in the reactor during the same time period. A fast-neutron reactor consumes about 1.07 grams of fissile material per megawatt-day thermal. *Phénix* generated an estimated 1.98 million MW-days until 1990 and therefore consumed about 2115 kg of fissile material. Combined with the reported breeding ratio of 1.16, these numbers can be used to estimate plutonium production available for weapons as about 340 kilograms.

Célestin. France operated two dedicated tritium-production reactors at Marcoule. These identical 190 MW (thermal) reactors came online in 1967 and 1968. When France decided to discontinue production of plutonium in 1992, the *Célestin* reactors began to operate in an alternating mode, with only one operating at a time. Both reactors were finally shut down on 23 December 2009, without much prior notice or further explanation. Reportedly, future tritium production will be carried out in a new naval test reactor (RES), which is under construction on the Cadarache site.

By the 1970s, it had become clear that the two *Célestin* reactors would produce more tritium than needed for the French nuclear arsenal. The mission then shifted from tritium production to the production of plutonium and special radioisotopes for both civilian and military purposes.[12] To estimate the contribution of the *Célestin* reactors to the French stockpile of weapons plutonium, we assume that large-scale plutonium production began when G2 and G3 were being prepared for shutdown. Between 1982 and 1991, the *Célestin* reactors together may have developed about 1.14 million MW-days. Assuming an effective production rate for plutonium of 0.6–0.7 g/MW-day, which would still allow for concurrent tritium production, this corresponds to 700–800 kilograms of plutonium.

Dual-use Gas-Graphite Power Reactors. In addition to its dedicated military reactors, France has also used its fleet of gas-graphite power reactors to produce plutonium for military purposes. Albright, Walker, and Berkhout have a rather detailed discussion of these reactors and their operational history. In principle, these reactors could have made a substantial contribution to the French stockpile of weapons plutonium.

The estimate summarized in Table 2 uses lifetime energy production values published by the IAEA for the six French and one French-supplied Spanish gas-graphite power reactors. Even for limited military usage fractions, these gas-graphite reactors would have produced about 1.7 tons of weapons plutonium. The uncertainty in this estimate cannot be specified with confidence based on the available information: if this production strategy proved "inconvenient" (e.g. led to disagreements with the operator EDF) or proved ultimately unnecessary, the reactors may not have been used for production of weapons plutonium in any systematic way—and their net contribution to the stockpile of weapons plutonium could be small.



	Reactor	Operation	Total Energy Developed	Usage Fraction	Weapon-grade Plutonium	Uncertainty
Marcoule	G1	1956–1968	0134 GWd	100 %	3.0–4.0 tons	±10 %
	G2	1958–1980	4450 GWd	100 %		±10 %
	G3	1959–1984				
	Célestin-1	1967–2009	n/a	1140 GWd	0.75 tons	±20 %
	Célestin-2	1968–2009				
	Phénix	1973–2009	2372 GWd	80 %	0.35 tons	±20 %
Total weapon-grade plutonium production at Marcoule					**4.6 ± 0.5 tons**	

Chinon	A1	1962–1973	500 GWd	(50 %)*	(0.20 tons)	large uncertainty depending on scope and extent of this strategy (if systematically pursued at all)
	A2	1965–1985	4150 GWd	(10 %)*	(0.38 tons)	
	A3	1966–1990	5090 GWd	(10 %)*	(0.46 tons)	
Saint Laurent	A1	1969–1990	7550 GWd	(1/3 of first core)	(0.13 tons)	
	A2	1971–1992	7820 GWd	(1/3 of first core)	(0.16 tons)	
Bugey	1	1972–1994	9220 GWd	(1/3 of first core)	(0.18 tons)	
Vandellos/Spain	1	1972–1990	8940 GWd	(1/3 of first core)	(0.17 tons)	
Potential weapon-grade plutonium production at other sites					**up to 1.7 tons**	

Table 2: Production of weapons plutonium in France. Estimating France's historic weapons plutonium production is difficult because a fleet of different reactor-types have been available for that purpose, including dual-use power reactors. In the early 1980s, France was planning to buildup its nuclear forces and may have considered these options. *Estimate.

Overall, cumulative production of weapons plutonium at Marcoule adds up to 4.6 ± 0.5 tons of plutonium. The total stockpile could be significantly higher if the gas-graphite power reactors played a significant role in the production program. In that case, the amount produced could have been significantly over 6 tons. We assume here a value of 7 ± 1 tons as the cumulative production of weapons plutonium.

Between 1960 and 1996, France conducted 210 nuclear weapon tests, which would have consumed about one ton of plutonium. The estimate for the current stockpile is therefore about 6 ± 1 tons. This is consistent with previous assessments, but with substantially different contributions from the different production reactors. This estimate is broadly in line with a leaked U.S. Department of Energy estimate published in 1999 that France had a stockpile of 6–7 tons of weapon-grade plutonium.

Conclusion

France has so far been extremely reluctant to make public any information about its military fissile-material stockpiles. France also has not officially declared any fissile material as excess for military purposes even though it must have significant amounts of both plutonium and HEU without apparent military use. Its nuclear arsenal is now half the size of the Cold War peak, and France no longer uses HEU for naval-reactor fuel. In fact, France has a declared total stockpile of fewer than 300 nuclear warheads, and these warheads are believed to have yields ranging from 100 to 300 kt. This arsenal of modern two-stage thermonuclear weapons would require about 3–6 tons of HEU and about 1.5 tons of plutonium.

Overall, France could therefore declare the larger part of its military HEU stockpile as surplus today, i.e., possibly have an inventory of excess HEU on the order of 20 tons out of the estimated inventory of 26 ± 6 tons. Similarly, France could declare almost 70% of its stockpile of weapon-grade plutonium as excess to military requirements (3.5–4.5 tons out of an estimated inventory of 6 ± 1 tons).

In March 2008, French President Sarkozy announced that he had "decided to invite international experts to observe the dismantlement of our Pierrelatte and Marcoule military fissile material production facilities."[13] A series of visits have taken place since then, but they apparently have not included any meaningful discussions about the possibility of verification of past fissile material production. As outlined in this paper, France would be in a unique position to support such an effort. On the one hand, the complex mode of operation of its production facilities in Pierrelatte and Marcoule make independent estimates of military fissile material inventories difficult. At the same time, the concentration of all production activities at these two sites makes it an ideal test case: France could partner with one or more countries in a verification exercise focused on these two sites and demonstrate new verification approaches for historic fissile material production. It would thus contribute to President Sarkozy's objective that "France could and should be more transparent with respect to its nuclear arsenal than anyone ever has been."

Endnotes

[1] An earlier but more extensively referenced version of this article appeared in *Global Fissile Material Report 2010: Balancing the Books,* December 2010, www.ipfmlibrary.org/gfmr10.pdf.

[2] At the time, the construction of plutonium production reactors at Marcoule was presented as a strategy to jumpstart the French nuclear power program, see "En 1958 Marcoule produira 100 kg de plutonium" (In 1958, Marcoule will produce 100 kg of plutonium), *Sciences et Avenir,* 109, March 1956, pp. 128–132; and also "Le drame du plutonium" (The plutonium drama), *Sciences et Avenir,* 135, May 1958, pp. 231–236.

[3] Bertrand Goldschmidt quoted an agreement signed in the aftermath of the crisis under which "the CEA was to carry out preparatory research into atomic explosions and, should the government then decide to proceed further, preliminary research leading to the production of prototypes and the staging of tests."

[4] Jean-Pierre Daviet, *Eurodif: Histoire de l'Enrichissement de l'Uranium (1973–1993),* Fonds Mercator, 1993.

[5] Daviet, 1993, op. cit., p. 169.

[6] Pierre Plurien and Jean-Hubert Coates, *La diffusion gazeuse in France, de Pierrelatte à Eurodif,* Uranium Enrichment Symposium, Pierrelatte, France, 20 March 1996, www.ipfmlibrary.org/plu96.pdf.

[7] Daviet, 1993, op. cit., p. 200.

[8] areva.com/EN/operations-792/eurodif-s-a-georges-besse-plant-uranium-enrichment.html

[9] David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies,* SIPRI, Oxford University Press, 1997, pp. 124–125.

[10] *Le Dossier Electronucléaire,* Syndicat CFDT (Confédération Française Démocratique du Travail) de l'Energie Atomique, Editions du Seuil, January 1980. For an excerpt, see www.ipfmlibrary.org/cfdt80.pdf.

[11] *French Nuclear Reactor Fuel Reprocessing Program,* Central Intelligence Agency, September 1984, released in July 1992, www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB184, mirrored at www.ipfmlibrary.org/cia84.pdf, p. 2.

[12] Les Réacteurs Célestin, *Bulletin d'Informations Scientifiques et Techniques (B.I.S.T.),* 153–154, Commissariat à l'Energie Atomique, November/December 1970, pp. 36–48, www.ipfmlibrary.org/cea70.pdf.

[13] Speech by President Nicolas Sarkozy, Presentation of SSBM Le Terrible in Cherbourg, 21 March 2008, www.ipfmlibrary.org/sar08.pdf.