# China's Historical Plutonium Production

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Abstract

This paper offers a re-evaluation of China's production of weapons-grade plutonium (WGPu) in order to estimate the maximum number of nuclear weapons that China can build using WGPu.[1] WGPu was produced in the 801 Reactor at the 404 Plant in Gansu Province (or the 404 Plant reactor) and the 821 Plant reactor in Sichuan Province. We review two existing estimates of WGPu production with widely varying methodologies and results: Zhang's 2017 estimate and Esin and Anichkina's 2013 estimate. In addition, we provide our own estimate based largely on the information in Zhang's paper, but with a reconsideration of Zhang's assumptions about the pace of production for 1980 and beyond and on his assumption about the closure date of the 821 Plant reactor.

Our primary findings suggest that Zhang and Esin and Anichkina essentially agree on the WGPu production in the 404 Plant reactor. We also find that Zhang and Esin and Anichkina differ dramatically on WGPu production in the 821 Plant reactor. Finally, we re-evaluated Zhang's estimate, focusing on his assumptions about production reductions after 1979 and the termination date for military production at the 821 Plant. This re-evaluation resulted in a 50 percent increase over Zhang's estimate, from 3,450 kilograms to 5,200 kilograms. Even taking account of losses for tritium production, processing and weapon fabrication, and nuclear testing, this increase could permit China to build, or have built, over 1,000 plutonium-based nuclear devices.

## Foundations of Fissile Material Production for China's Nuclear Weapons Program

On January 15, 1955, the Chinese Communist Party (CCP) of the People's Republic of China (PRC) committed to building an atomic bomb.[2] Initially acting with technical and expert assistance from the Soviet Union, China proceeded along two lines in the production of fissile material for nuclear weapons.[3] Highly-enriched uranium (HEU) was to be produced at a gaseous-diffusion enrichment plant to be built at a site near Lanzhou that was originally intended for an aircraft construction factory. Plutonium was to be created and separated at a newly built plant with a light-water-cooled, graphite-moderated production reactor and reprocessing plant located in the Gobi Desert near the city of Yumenzhen in Jiuquan Prefecture.

When Moscow withdrew its experts in August 1960, the building for the enrichment plant was complete and largely equipped for operation. Construction of the plutonium production reactor, on the other hand, was at a much earlier stage. The foundation was complete and the concrete baseplate for the reactor core was in place. Production of HEU was therefore prioritized, slowing the construction of the plutonium infrastructure while China proceeded to its first test of an HEU-based nuclear explosive on November 16, 1964.[4] Notably, the uranium core for the device was machined and prepared at the 404 Plant near Yumenzhen in late April of that year.[5]

With HEU production rounding into shape, work shifted back to plutonium production at the 404 Plant near Yumenzhen.[6] Revisions to the production reactor design were completed in April 1963. The installation of the graphite bricks for the reactor itself began in the spring of 1966. The reactor first achieved criticality on October 20, 1966.

The production reactor at the 404 Plant was the first of two that China operated, with collocated reprocessing plants to support its nuclear-weapon program. A second production reactor was at the 821 Plant near Guangyuan in Sichuan Province. Construction of another underground facility with a plutonium-production reactor and collocated-reprocessing plant was started at the 816 Plant near Fuling in the Chongqing Municipality, but delays associated with building the underground facility led to its cancellation prior to completion.[7]

In the following sections, we examine two estimates of the mass of WGPu produced by China beginning in 1966 until China reportedly halted production in the late 1980s or early 1990s.[8] First, we examine the work of Zhang Hui, who has authored multiple assessments of China's stocks of WGPu.[9] Second, we review Viktor Esin and Tatiana Anichkina's 2013 assessments for the Potomac Foundation.[10] While there is some overlapping information in these assessments, the authors rely on uniquely different sources resulting in dramatically different numbers. Third, we re-examine some of Zhang's assumptions to produce what we believe is an upper limit on China's WGPu production.

## The 404 Plant

The 404 Plant is located off the main highway running between the cities of Yumenzhen, Jiayuguan, and Jiuquan. Workers were moved from the original plant site to a new residential area in Jiayuguan in 2006 and now commute by train from the city to work, where the former plutonium production area is located, along with the reprocessing buildings.[11]

According to Chinese bloggers, water was brought to the site beginning in 1959 through a 52-kilometer pipeline.[12] Based on Google Earth imagery, there is one major dam, on the Changma River, southwest of Yumenzhen at roughly the indicated distance from the plant site. About five kilometers downriver from the main dam, in Google Earth we observed what appears to be the beginning of the pipeline to the 404 Plant with features identical to those depicted in a video entitled "China Nuclear City 404."[13]

Zhang and other analysts rely heavily on the 1987 China Today account of China's early nuclear fuel cycle and weapons developments.[14] According to that account, after the reactor first achieved criticality on October 20, 1966, reactor power reached the specified 0.5 percent level for the first time on December 31, 1966. From there, power was increased gradually, and the reactor began stable operations. The report broke the operational history from 1967 to 1985 into three periods.

From 1967 to the first half of 1975, the operators renovated reactor elements, accumulated operating experience, and attained the design rated output. According to a Chinese-language technical publication, the design power was 600 MWt (which was not reported in the 1987 China Today account).[15]

Reactor technical failures were a particular problem until 1970, when operators determined a way to keep the reactor running while technical failures were being cleared, which they began to implement. One such failure, due to core and fuel swelling, resulted in the meltdown of an aluminum channel liner and the fuel elements in it on January 7, 1969.[16] It took 20 hours of work in a high radiation environment to clear the blockage, an event commemorated in a relief displayed in the 404 Plant museum.

On December 30, 1973, the reactor was shut down to repair a leak first discovered in its load-bearing protective water container in October 1972. The reactor was restarted after a delay of over six months. In the first half of 1975, the reactor reached its design power, presumably 600 MWt, for the first time. From the second half of 1975 to 1980 (the last year of China's 5th Five-Year Plan), the pursuit of research and technical innovations became focal areas. Beginning in the second half of 1975, production capacity uniformly exceeded the original design goals. An increased goal was set for production, involving increased fuel burn-up and an increase in operating days from 288 to 324 days per year.[17] As we discuss in the appendix, the new goal for production was 1.2 times the original goal. Since the increase in operating tempo from 288 to 324 days is only a 13 percent increase, we infer that the new goal likely involved a power increase as well. Also, during this period, in June 1968, a tritium production line was built at the site.[18]

Beginning in 1981, the period of the 6th Five-Year Plan, additional uses were found for the reactor, including dual-purpose technologies, especially for production of electrical power from the reactor. The China Today (1987) document provides much less detail about plutonium production during this period, with the account only extending to about 1983. At the fourth meeting of the reactor operators exchange in March 1981, multipurpose uses became a primary 6th Five-Year Plan goal for the reactor, especially conversion of the reactor to a dual-purpose facility producing both plutonium and electricity. To support the new reactor operating parameters, the fuel element producer developed a new fuel casing and the provider of the technical aluminum tubes in the reactor developed a new product, both of which were tested in the 404 Plant reactor.

Enhanced reactor monitoring and additional research indicated that the 15-year lifetime of the reactor, as of 1981, could be extended to 30 years. Based on initial discussions in 1982, the Beijing Academy of Nuclear Engineering Research and Design commenced preliminary work on conceptual and construction designs for the generation of electricity with the reactor in 1983.

We note that there is no available imagery evidence that the reactor ever provided electricity to the site. By 2017, well after the nuclear reactor was shut down, a much larger coal-fired electrical generation capacity was built at the site in another area near the reactor and reprocessing area. Although the China Today account provides no information about the shutdown of the reactor, a blogger recounted a visit with regional dignitaries to the reactor on November 8, 1986, where it was declared that the reactor had completed its mission.[19]

Relying on the efficiency of the PUREX process the Chinese used in the reprocessing of the spent fuel, we assume that virtually all of the WGPu made in the reactor was recovered. Zhang modeled WGPu production in the 404 Plant reactor as follows:[20]

• From 1967 through 1973, the reactor power increased linearly from 0.5 percent of design power to about 85 percent of the design power of 600 MWt.
  - The capacity factor[21] during 1967–69 was assumed to be 40 percent.
  - The capacity factor during 1970–73 was assumed to be 80 percent (288 days per year).

• The reactor was shut down for 103 days, January 1974–April 1974, for repair and maintenance.

• From April 1974 through June 1975, the reactor power increased linearly to the full design power of 600 MWt with a capacity factor of 80 percent.

• From July 1975 through 1979, the reactor linearly increased its plutonium-production rate to 1.2 times the initial design production rate.

• From 1980 until shutdown in November 1986, the plutonium-production rate was about half of that in 1979.

Zhang assumed that WGPu was produced at the rate of 0.9 grams of WGPu per MWt-day of fuel burn-up. Employing continuous piecewise-linear fits to Zhang's model, we calculated the yearly production as shown in Figure 1, which apparently agrees with Zhang's 2017 paper. In Figure 2, we sum up the yearly production to show cumulative WGPu production in the 404 Plant reactor, which totals about 2,000 kg.

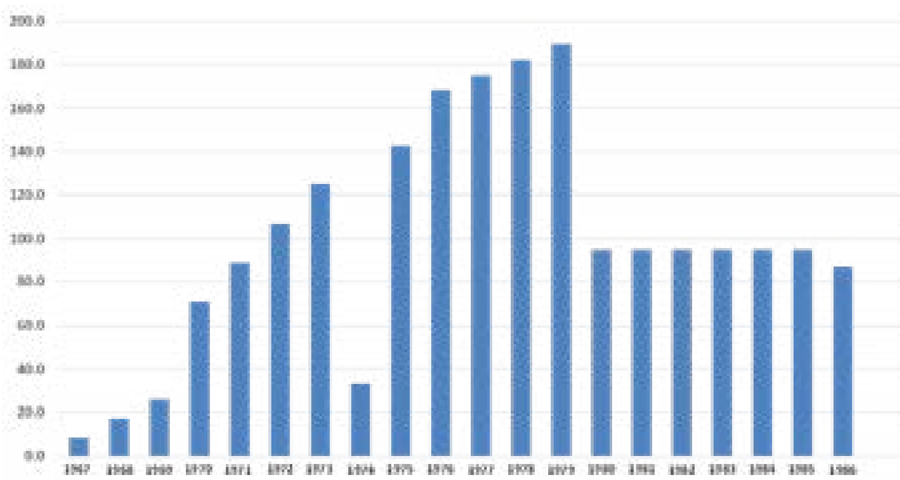

**Figure 1. Yearly production of WGPu, in kilograms, in the 404 Plant reactor according to Zhang's model.**

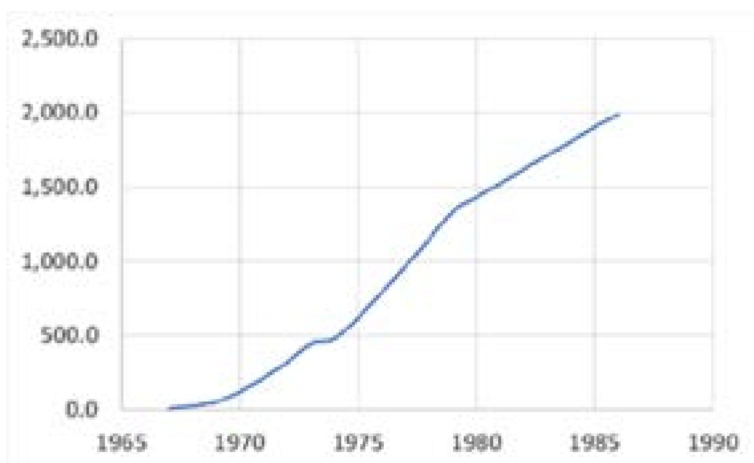


**Figure 2. Cumulative WGPu production, in kilograms, in the 404 Plant reactor, from Figure 1.**

## The 821 Plant

The 821 Plant was built in northern Sichuan Province as part of the overall construction of Third Line facilities, defense-oriented facilities and companies that were built to reduce the threat of foreign attack by siting them farther from China's borders in deep ravines and in underground facilities.[22] Construction of the 821 Plant began in October 1969.

Unlike the 404 Plant, which came first and was more exhaustively discussed in *China Today*, information on the 821 Plant comes almost exclusively from reminiscences and blogs written by former employees. The plant is located on the Bailongjiang River, a small tributary of the Bailong River separating the plant from the residential area in Sanduizhen. The production reactor is downriver and to the east of the reprocessing building. As indicated elsewhere, this Third Line plant was built in an area heavily cut by deep ravines. The reactor is cooled with river water, likely from the Bailongjiang; the larger Bailong is just over two kilometers away. Reportedly, the river water drawn by the reactor was clouded with particulates that presented a problem for the outer cooling loop, especially in the summer when the river was lower.[23] The area adjacent to the reactor building was designated for water treatment according to Zhang.[24]

The production reactor was first started in December 1973, and stable, full-power operation was achieved on October 11, 1974.[25] As mentioned previously, based on a Chinese technical publication, we assess that full power was 600 MWt.[26] From there, the "1.3 reactor" target was reached in 1978, presumably production at a level thirty percent greater than that originally planned. At the same time, reportedly due to the demands posed by a dangerous international situation, the 404 Plant reactor was producing at 1.2 times the original goal, so that the two production reactors were referred to as the "2.5 reactor."[27] The higher production was attributed to "deepening fuel consumption and strengthening power." Presumably, this meant increasing fuel burn-up and the reactor power.

The reprocessing plant commenced production in 1976, and WGPu was apparently produced in May of the same year. In 1977, the reprocessing plant reached the expected production capacity.[28]

The plant continued to produce WGPu until sometime in the 1980s. In the early 1980s, China's nuclear industry began a shift from a military-only posture to a mixed military-commercial model.[29] In June 1982, the 816 Plant project was suspended and terminated two years later. Also in 1982, the 827 Plant project, which was to build a pair of heavy-water reactors and a processing plant at an underground site near Yichang on the Yangtze River, perhaps to produce tritium, was terminated.[30] According to one source, facing a reduced threat in the world, China's State Council decided in August 1987 to "stop production of military products and switch to civilian products" at the 821 Factory.[31] A separate source recorded that military production at the factory was halted in 1988.[32]

In modeling WGPu production at the 821 Plant, Zhang broke production into four time periods:

• December 1973 to October 1974, during which reactor power rose linearly to the design power of 600 MWt with a capacity factor of 40 percent.

• November 1974 to December 1976, during which the reactor operated at 600 MWt with a capacity factor of 80 percent.

• January 1977 to December 1978, over which period the plutonium-production rate increased linearly to 130 percent of the originally designed value—maintained until December 1979.

• From 1980 until shutdown for conversion in August 1984, during which the plutonium-production rate was half that in 1979.

Again, assuming that WGPu was produced at the rate of 0.9 grams of WGPu per MWt-day of fuel burn-up, we calculated the yearly production of the 821 Plant according to Zhang's model as shown in Figure 3. In Figure 4, we sum up the yearly production to show cumulative WGPu production in the 821 Plant reactor according to Zhang's model, which totals up to about 1,450 kg.

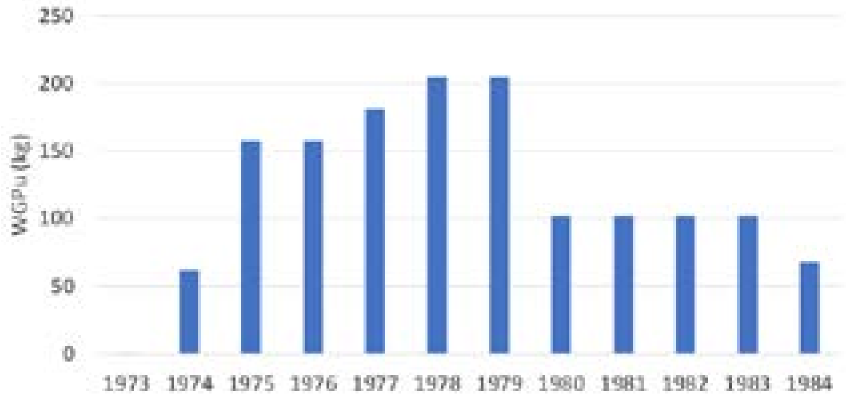


**Figure 3. Yearly WGPu production at the 821 Plant reactor according to Zhang's model.**

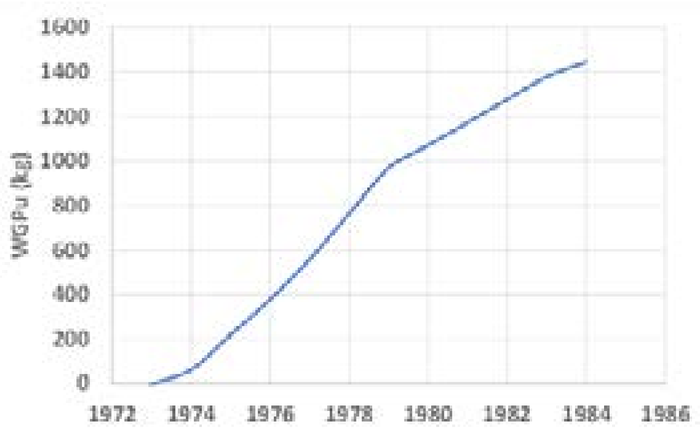


**Figure 4. Cumulative WGPu production at the 821 Plant reactor from Figure 3**

## Review of Esin and Anichkina's Assessment

Esin and Anichkina produced an assessment that they compared to Zhang's 2011 assessment of WGPu production.[33] Zhang's 2011 assessment used a reactor power of 250 MWt for both the 404 Plant and 821 Plant reactors (versus the 600 MWt used in his 2017 assessment and here). Citing informal contacts between Esin and two unnamed scientists who worked for the Dollezhal Scientific Research and Development Institute for Electric Power (NIKIET is the Russian acronym) in the late 1950s and worked with the Chinese on the design of the 404 Plant reactor, Esin and Anichkina employed a reactor power of 500 MWt.[34] Esin and Anichkina also employed the same temporal profile for WGPu production in the 404 Plant reactor as Zhang (in 2011), which differs from Zhang's 2017 assessment discussed here in two respects: (1) the reactor is assumed to have shut down two years earlier, in 1984, and (2) WGPu production is assumed to have held at the peak value until shut down (as opposed to here, using Zhang's model, where production was halved after reaching a peak).

Taking account of some competing factors, Esin and Anichkina assessed that the 404 Plant reactor produced 1,800 kg of WGPu versus the 2,000 kg Zhang assessed in 2017. Given that Esin's unnamed former NIKIET scientists claimed that the 404 Plant reactor had a power of "not less than 500 MWt," Zhang's 2017 assessment and Esin and Anichkina's are essentially the same.

Esin and Anichkina produced a much larger assessment for WGPu production in the 821 Plant reactor. As of the writing of their 2013 report, they stated that the 821 Plant reactor as still running, citing only the website of the Center for Energy and Security Studies in Moscow, with no further information. Further, citing three unnamed scientists from Moscow's Kurchatov Institute who claimed to have personally participated in Russian assistance to the developing Chinese complex, Esin and Anichkina write that they were informed that (1) the 821 Plant reactor had an operating power of 850 MWt, (2) was capable of producing 280 kilograms of WGPu per year, and (3) by 1990, could have produced up to 4.5 tons of WGPu. They also added that the reactor was shifted to tritium production at that time, but that it was capable of producing an additional 2.9 tons of WGPu by 2009 employing intermittent short production campaigns.

Based on these estimates, the total value grew to as much as 7,400 kilograms of WGPu produced in the 821 Project reactor. This is a dramatic increase over the 1,450 kilograms assessed by Zhang. We note the conditional nature of Esin and Anichkina's estimate and assess it possible that the operating power of the reactor could have increased to 850 MWt. However, the discussion in the appendix provides more than one piece of evidence pointing to an original design power of 600 MWt, with an increase in power or WGPu production more generally by an additional 30 percent. We are somewhat skeptical of Esin and Anichkina's estimate for several reasons:

• At a production rate of 0.9 grams of WGPu per MWt-day of fuel burn-up, even accepting an operating power of 850 MWt, yearly production of 280 kilograms of WGPu requires full operation of the reactor, 365 days per year. Practically, this is impossible, given the time required for maintenance and fuel changeout.

• Alternatively, assuming a capacity factor of 90 percent, with the 404 Plant reactor reaching 328 operating days per year, a production rate of about 1.0 grams of WGPu per MWt-day of fuel burn-up is required. This number is higher than the 0.8-0.9 grams per MWt-day from most production reactors.[35] However, the French G1 production reactor approached it, with a reported production rate of 0.95 grams per MWt-day.[36]

• Production of WGPu to 1990 and beyond contradicts two apparently independent sources who claim military production in the 821 Plant reactor ended by 1988.

The production of an additional 2.9 tons of WGPu by 2009 would represent a significant expenditure of effort on what we infer was not the primary focus of reactor operations in that time period. On average, over the 19 years from 1990 to 2009, the reactor would need to produce over 125 kilograms of WGPu per year. Even at 850 MWt, assuming 0.9 grams/MWt-day, the reactor would have to devote an average of 163 days per year to WGPu production.

**Reassessing China's WGPu Production in the 404 Plant and 821 Plant Reactors**

In our reconsideration of Zhang's assessment, we judge that Zhang's assumption that both reactors halved production in their later years of operation deserves reconsideration. There is no firm confirmation of this assumption, which is based on Zhang's belief that there was a general shift in China's nuclear program in the early 1980s. That shift moved away from the purely military to a greater commercial orientation, which led to a reduction in WGPu production. Additionally, while Zhang assumed that the 821 Plant reactor shut down in August 1984 for conversion, presumably to non-military use, we note that two separate sources (1) claimed that China's State Council decided in August 1987 to "stop production of military products and switch to civilian products" at the 821 Factory,[37] and (2) that military production at the factory was halted in 1988.[38] This acknowledges that neither of these claims is unambiguous about the date of the reactor shutdown, since the reactor may have shut down earlier, while the reprocessing plant may have continued to reprocess spent fuel for WGPu until the latter dates. However, for comparison, we assume that the 821 Plant reactor continued to produce WGPu until the end of 1987. Our results are as follows:

• For the 404 Plant reactor, assuming it continued to produce WGPu at the 1979 peak rate of 190 kilograms per year until November 1986 (prorated to 174 kilograms in that last year) results in about 660 additional kilograms of WGPu and a total of over

2,600 kilograms.

- For the 821 Plant reactor, assuming that it ran continuously to the end of 1987 at the peak 1979 production rate of 205 kilograms per year, results in an additional production of almost 1,200 kilograms and a total of just over 2,600 kilograms.

This results in a total of over 5,200 kilograms for the two reactors.

## Conclusion: Implications of the Different Assessments

Table 1 summarizes the three assessments of China's production of WGPu in the 404 Plant and 821 Plant reactors. In summary, the difference between Zhang's 2017 assessment and our reassessment in this paper stems directly from Zhang's undocumented assumption that from 1980 onward WGPu production was halved in both reactors based on a general shift away from a purely military nuclear industry to a mixed military-commercial model. In our reassessment, it is assumed that production proceeded at the 1979 peak value until shut down. The closure date for the 821 Plant reactor from Zhang's inferred, but not confirmed, year of 1984, is extended to 1987, when military production was said to have ended.

| Zhang (2017) | Swegle and Yeaw | Esin and Anichkina |
|---|---|---|
| | 404 Plant | |
| 2,000 kg | 2,600 kg | 1,800 kg |
| | 821 Plant | |
| 1,450 kg | 2,600 kg | 4,500 kg (possible, to 1990) |
| | | 2,900 kg (possible, 1990-2009) |
| | Totals | |
| 3,450 kg | 5,200 kg | 6,300 to 9,200 kg |

**Table 1. Assesments of China's production of WGPu at the 404 Plants and 821 Plants**

The difference between Zhang's assessment and that of Esin and Anichkina results from totally different analyses of the 821 Plant reactor. The two differ in three respects:

1) While Zhang relied on published Chinese sources and personal accounts from Chinese workers at the 821 Plant, Esin and Anichkina appear to draw heavily on personal discussions with three unnamed scientists from Moscow's Kurchatov Institute who claim to have personally participated in Russian assistance to the developing Chinese complex.

2) Esin and Anichkina employed a much higher reactor power of 850 MWt for the 821 reactor versus the 600 MWt offered by Zhang. The lower value was drawn from a 1990 report, described above, which discussed a 600-MWt reactor in terms that implicitly referred to all three reactors at the 404 Plant, 821 Plant, and 816 Plant. Without regard to the actual power level, Zhang, unlike Esin and Anichkina, argues that mentions of 1.2, 1.3, and, in combination, 2.5 reactors imply a common design power level for the reactors.

3) Esin and Anichkina suggest that the 821 Plant produced WGPu well beyond the dates provided by other independent sources.

We judge that the rather conditional nature of Esin and Anichkina's assessment, and the problematic nature of some of their quantitative analysis, makes their assessment less reliable.

In closing, we focus on Zhang's 2017 assessment and our reassessment here and consider the numbers of potential nuclear devices. According to Zhang's methodology for loss of WGPu to tritium production, processing and fabrication, and nuclear testing, his original estimate of 3.4 tonnes of WGPu produced is reduced to a central value of 2.9 tonnes available for nuclear weapons. Applying a similar methodology, our estimate of WGPu available for weapons is reduced to about 4500 kg. We offer two values for the WGPu per weapon. At the upper end, 6 kilograms of WGPu is employed—similar to the Fat Man bomb dropped on Nagasaki.[39] At the lower end, 4 kilograms of WGPu is used—consistent with Zhang.[40] Table 2 shows the numbers of possible nuclear devices.

| | Zhang's 2017 assessment (2,450 kg) | Our reassessment (4,500 kg) |
|---|---|---|
| 6 kg per device | 400 | 750 |
| 4 kg per device | 600 | 1,125 |

**Table 2. Numbers of possible nuclear devices**

## Appendix: Design Power of China's Original Plutonium Production Reactors

The China Today article referenced in the body of this article provides extensive information on timelines and the qualitative operating profile of the 404 Plant reactor; however, it fails to provide the design power of the reactor, which is needed to estimate plutonium production.[41] The thermal design power is given in a 1990 technical publication as 600 MWt.[42] The reactor is also said to have an electrical power of 100 MWe, which implies a thermal-to-electrical conversion that is quite low by comparison with the roughly 30 percent of a dedicated power plant. Although we see no visual evidence of electrical transmission equipment at the 404 Plant reactor building, the low thermal-to-electrical efficiency indicates a lower-temperature core suited to the use of metallic, as opposed to oxide, reactor fuel, as well as targets, if any.

The same article implies that the reactors at the 404 and 821 Plants are basically the same, and the same as that intended for the cancelled 816 Plant. The article mentions one power level, but three reactors "located in a desert area [404 Plant], ravine area [821 Plant], and cave body [816 Plant]." Additional information suggests they have the same power.

Less conclusively, because it does not refer to the reactor directly, a Chinese blogger who worked at the 821 Plant (and referred to the site as "the ravine") wrote that in 1969, the central government shifted equipment planned for installation on the 816 project to build the 821 Plant.[43]

Zhang also took note of the implied math in the commentary of workers from the sites, which also points to both operating reactors having the same design power.[44]

- According to a memoir from Zhou Zhi, former Deputy Minister of the Second Ministry of Machine Building Industry, after reaching design power, the 404 Plant reactor reached a production level to 1.2 times the original design value.[45]
- Two other blogs stated that the 821 Plant reactor increased production to 1.3 times the original design value.[46]
- A blog also indicated that the two reactors were directed by the head of the Second Ministry of Machine Building Industry to produce at a level of 2.5 reactors, i.e., the sum of 1.2 and 1.3 for the pair. Zhang took that straightforward summation to indicate that both reactors had the same original design power.

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1. Plutonium is used in a stand-alone "atomic bomb" or in the first stage of a multi-stage thermonuclear weapon.

2. Robert S. Norris, "Selections from 'China Today: Nuclear Industry,'" Security Dialogue, 27, no. 1 (1996), 39-54. See also, Foreign Broadcast Information Service, JPRS-CST-88-002 (Springfield, VA: Department of Commerce, 1988), 42-45, 64-74, 166-184, 195-197, 201-202, 204-215, 227-239, 255-256, 258-263.

3. Apparently, the plan was always to produce thermonuclear devices using both materials.

4. Norris, "Selections from 'China Today: Nuclear Industry,'" 39-54.

5. Zeng Wan, "Heroes Don't Ask Guys," Sina Blog (2014), http://blog.sina.com.cn/s/blog_4fe086bc0102v5jw.html. See also Zeng Wan, "The landlord" (November 2015) http://blog.sina.com.cn/s/blog. See also "Little white rabbit early nuclear reactor," http://www.9ifly.cn/thread-6005-1-1.html. See Wayback Machine: https://web.archive.org/web/20190328133210/http://www.9ifly.cn/thread-6005-1-1.html.

6. Although these different sites and plants each go by more than one name, here we will refer to them by their assigned number.

7. "Exploring the 816 nuclear plant: an underground nuclear project that was built and stopped for peaceful construction," Sina Finance, November 15, 2017, http://finance.sina.com.cn/roll/2017-11-15/doc-ifynwhww5164483.shtml (original in Chinese).

8. Weapons-grade plutonium is defined in terms of the ratio of the isotopes Pu-239 and Pu-240, the former being the desirable fissile material for weapons and the latter a more radioactive isotope that can cause pre-detonation of an imploding assembly at lower than desired yields. A ratio of six percent is typically regarded as the desirable limit for the ratio of Pu-240 to Pu-239 in a nuclear weapon, although even higher ratios can be employed in certain designs.

9. International Panel on Fissile Materials, Global Fissile Material Report 2010 (Princeton: International Panel on Fissile Materials, 2010), 97-106. See also Hui Zhang, "China's HEU and Plutonium Production and Stocks," Science & Global Security, 19 (2011), 68–89; Hui Zhang, "The History of Fissile Material Production in China," Nonproliferation Review, 25 (2018), 477-499; and Hui Zhang, China's Fissile Material Production and Stockpile (Princeton: International Panel on Fissile Materials, 2017).

10. Victor Esin and Tatiana Anichkina, "Production and Stocks of Nuclear Weapons Fissile Material in China," Potomac Technical Memo: No. 13-07 (Vienna, VA: Potomac Foundation, 2013).

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13. "China Nuclear City 404" (中国核城404), released 18 August 2018, accessed 8 January 2021, Tencent Video, https://v.qq.com/x/page/y0758yrxjzz.html.

14. Foreign Broadcast Information Service, "Selections from 'China Today: Nuclear Industry,'" 42-45, 64-74, 166-184, 195-197, 201-202, 204-215, 227-239, 255-256, 258-263.

15. Huang Jianchi and Xi Lisheng, "Development of Production Reactors in My Country," Advances in Earth Science, no. 2, (1990), 60-61.

16. Li Jie, "A Major Nuclear Accident at China Nuclear Power Plant 404," August 14, 2006, Newsmth, https://m.newsmth.net/article/MilitaryView/229471.

17. Increasing fuel burn-up, measured in megawatt-days, increases the undesirable pluto-

nium-240 isotopic content of the fuel, relative to that of the desirable plutonium-239 content; however, it is a matter of designer judgment to decide an allowable plutonium-240 content, which will never be zero.

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