CHINA'S HISTORICAL PLUTONIUM PRODUCTION

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EXECUTIVE SUMMARY

In this paper, we reevaluate China's production of weapons-grade plutonium (WGPu) in order to estimate the maximum number of nuclear weapons using WGPu that China could build.† This 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. Both are graphite-moderated, light-water-cooled production reactors that began operation in late 1966 and late 1973, respectively, and both have been shut down for decades (with the date of termination at issue between different authors). We know of no openly available information indicating that China has resumed WGPu production elsewhere.

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 are the following:

- Zhang and Esin and Anichkina essentially agree on the WGPu production in the 404 Plant reactor, with a small difference largely due to Zhang's 600 MWt reactor power, based on a 1990 Chinese-language publication, and Esin and Anichkina's 500 MWt reactor power, based on proprietary conversations with Russian scientists who claim to have worked with the Chinese prior to a break between the Soviet Union and China.

- Zhang and Esin and Anichkina differ dramatically on WGPu production in the 821 Plant reactor. Zhang relied on information from former plant workers and assumptions based on the political context with regard to nuclear power at the time in China. Esin and Anichkina relied heavily on proprietary discussions with Russian scientists who claimed to have personally participated with the Chinese in developing their nuclear complex. Esin and Anichkina's estimates were more conditional, and they employed a much higher reactor power and the assumption that the reactor continued to produce WGPu well after former Chinese workers claimed production had ended. Ultimately, we found quantitative elements of the Russian estimate, which was much larger than Zhang's, to be problematic.

- We reevaluated Zhang's estimate, focusing on his assumptions about production reductions after 1979 and the termination date for military production at the 821 Plant. This reevaluation resulted in a 50 percent increase over Zhang's estimate, from 3,450 kilograms to 5,200 kilograms. This increase could permit China to build, or have built, over 1,000 plutonium-based nuclear devices.

† Plutonium can be used in a stand-alone "atomic bomb," or it can be used in the first stage of a multi-stage thermonuclear weapon.

CONTENT

This paper relates closely to research the authors conducted for the National Strategic Research Institute (NSRI) at the University of Nebraska, but the conclusions in this report reflect the authors' personal views. The data sources supporting this paper are all unclassified and publicly available.

The Authors

John Swegle has extensive experience at Department of Energy national laboratories assessing nuclear weapons capabilities of various countries. Christopher Yeaw has extensive experience in both foreign analysis and the direction of nuclear security programs for the U.S. government.

FOUNDATIONS OF FISSILE MATERIAL PRODUCTION FOR CHINA'S NUCLEAR WEAPONS PROGRAM

On 15 January 1955, China committed to building an atomic bomb.[1, 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.[‡] Highly-enriched uranium (HEU) was to be produced at a gaseousdiffusion enrichment plant to be built at a site near Lanzhou that was originally intended for an aircraft construction factory, and plutonium was to be created and separated at a newly-built plant with a lightwater-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 basically complete, and the concrete baseplate for the reactor core had just been placed. 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 16 November 1964.[3] Notably, the uranium core for the device was machined and prepared at the 404 Plant near Yumenzhen in late April of that year.[4,5]

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

The production reactor at the 404 Plant was the first of two that China operated – both now shut down – with collocated reprocessing plants to support its nuclear-weapon program. The second 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. **Figure 1** shows the locations of these three plants, and **Figure 2** provides a timeline. We consider the production complexes in the time order shown in the timeline.

In the following sections, we examine two estimates of the mass of WGPu[**] produced by China from this beginning in 1966 until China reportedly halted production in the late 1980s or early 1990s. The first is from Zhang Hui, currently a Senior Research Associate in the Program on Managing the Atom at Harvard's Belfer Center, who has authored multiple assessments of China's stocks of WGPu.[6,7,8,9] Our review here is largely based on the 2017 report that is likely his most comprehensive to date, China's Fissile Material Production and Stockpile,[10] and supporting references. The second is from Viktor Esin, former Chief of the Main Staff of the Russian Strategic Rocket Forces and Professor at the Russian Academy of Military Sciences, and Tatiana Anichkina's 2013 assessments for the Potomac

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

§ Although these different sites and plants each go by more than one name, here we will refer to them by their assigned number, e.g., the 404 Plant. In this system, the uranium enrichment plant near Lanzhou is the 504 Plant.

** 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.

Foundation.[11,12] While there is some overlapping information underlying these second assessments, there are also some uniquely different information sources resulting in dramatically different numbers.

Finally, we re-examine some of Zhang's assumptions to produce what we believe is an upper limit on China's WGPu production based on his basic information sources.

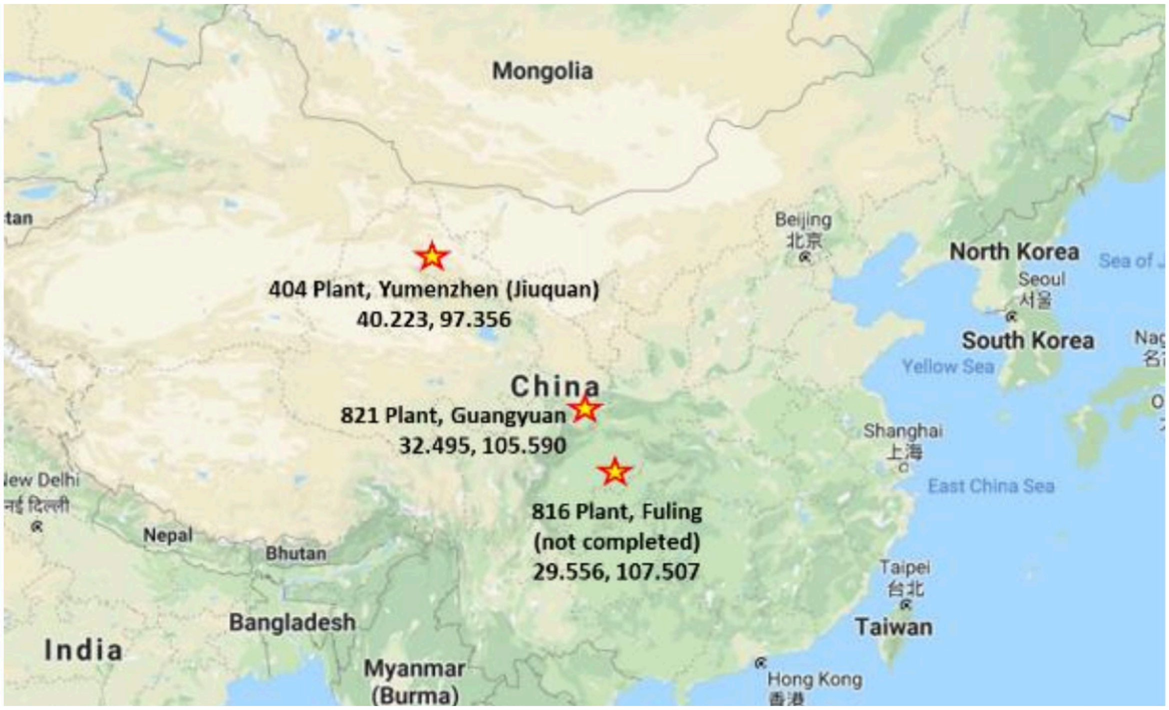

Figure 1. Locations and coordinates of the two now-decommissioned plutonium production plants and the underground production plant that was not completed.

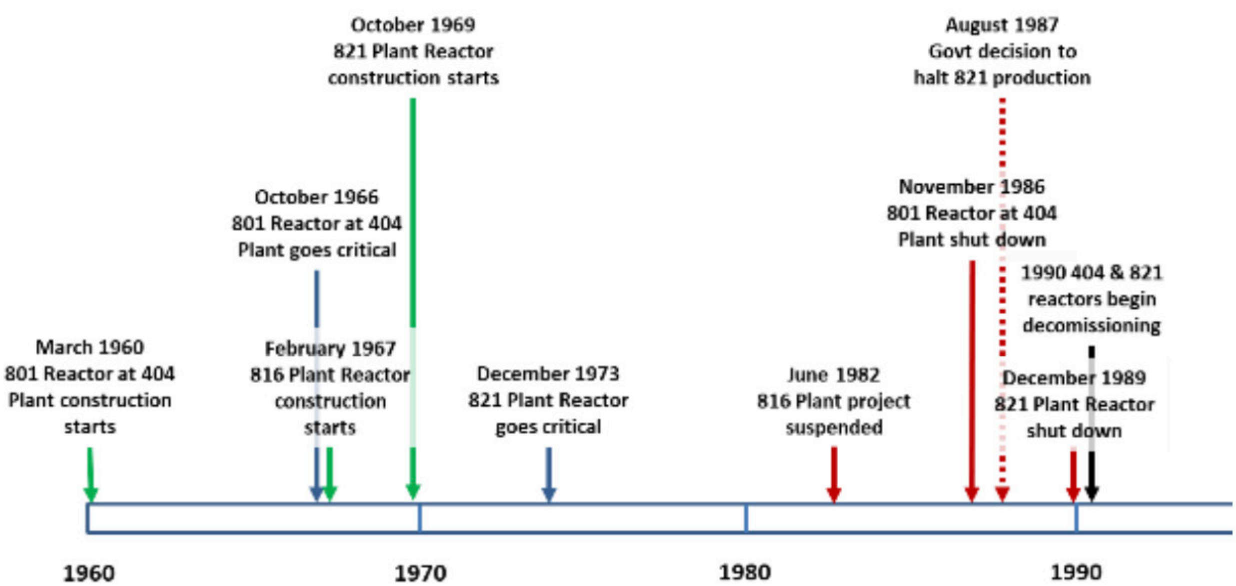

Figure 2. Timelines for China's plutonium production complexes.

REVIEW OF ZHANG'S ASSESSMENT

The 404 Plant

The 404 Plant is located off the main highway running between the cities of Yumenzhen, Jiayuguan, and Jiuquan, as shown in **Figure 3**. The plant site is shown in **Figure 4**, where we've highlighted the old 404 city (workers in that city were moved to a new residential area in Jiayuguan in 2006[13] and

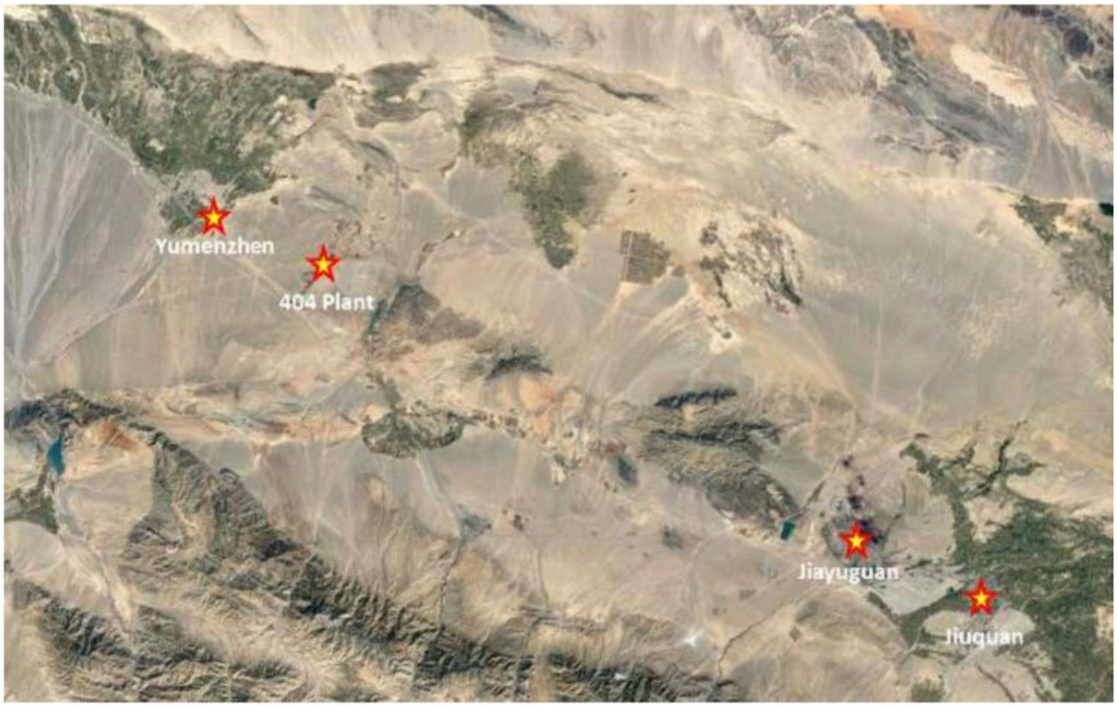

Figure 3. Location of the 404 Plant relative to the nearby cities in Gansu Province.

Figure 4. Overview of the 404 Plant site.

now commute to work by train from the city), and the area where the former plutonium production area is now located, along with the reprocessing buildings. Figure 5 shows the reactor and reprocessing area in more detail (albeit from imagery taken almost 40 years after the plutonium production reactor was started).

Figure 5. Detail of the 404 Plant reactor and reprocessing area. The Assembly building is the one in which the original nuclear weapon parts were prepared for China's first nuclear test.

According to Chinese bloggers, water was brought to the site beginning in 1959 through a 52-kilometer pipeline.[14,15] We find one major dam, on the Changma River, somewhat to the southwest of Yumenzhen, on the circumference of a 52-kilometer-radius circle with the 801 Reactor at its center. Roughly 5 kilometers further downriver from the main dam, we see what is likely the beginning of the pipeline to the 404 Plant. In Figure 6, we show overhead imagery of the probable pipeline, and in Figure 7, we show a screen capture of the beginning of the pipeline from a Chinese video of the history of the 404 Plant.[16]

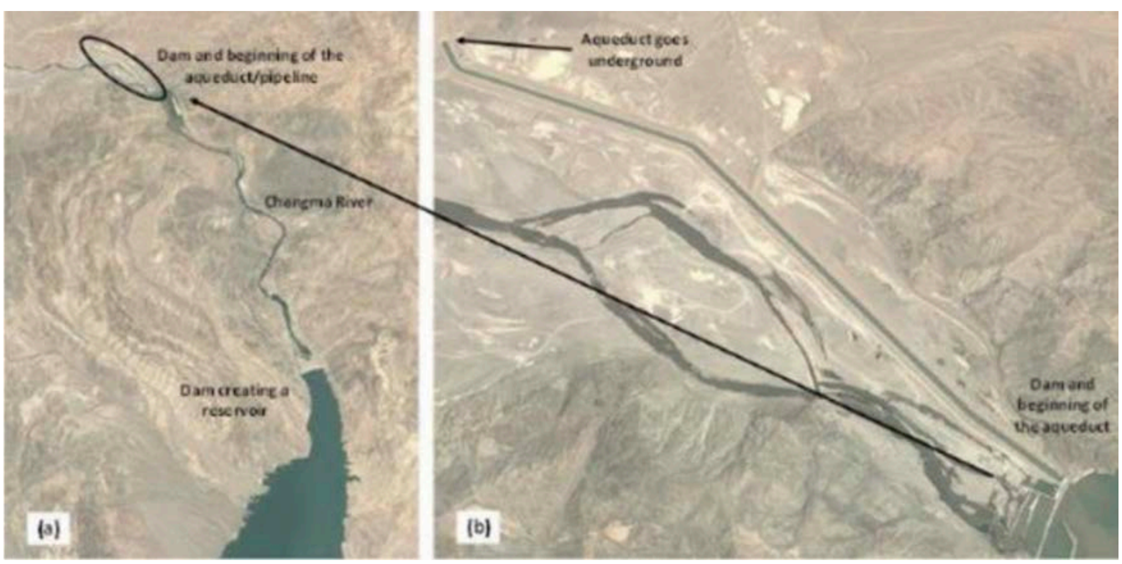

Figure 6. Likely location of the beginning of the aqueduct and pipeline carrying water from the Changma River, roughly southwest of Yumenzhen, to the 404 Plant. The locations are 50-some kilometers from the plant, as described in the blog of a former worker. (a) An overview, and (b) a closeup of the beginning of the aqueduct and pipeline.

Figure 7. Screen capture of the beginning of the 404 Plant aqueduct and pipeline on the Changma River, from the Chinese-language video, China Nuclear City 404.

Zhang and other analysts rely heavily on the 1987 *China Today* account of China's early nuclear fuel cycle and weapons developments.[17] According to that account, after the reactor first achieved criticality on 20 October 1966, reactor power reached the specified 0.5 percent level for the first time on 31 December 1966. From there, power was increased gradually, and the reactor began to operate stably. The account 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).[18] The top of the reactor core is shown in **Figure 8**, and the reactor control room is shown in **Figure 9**.[19]

Figure 8. Screen capture of the top of the 404 Plant plutonium-production reactor, from the Chinese-language video, China Nuclear City 404.

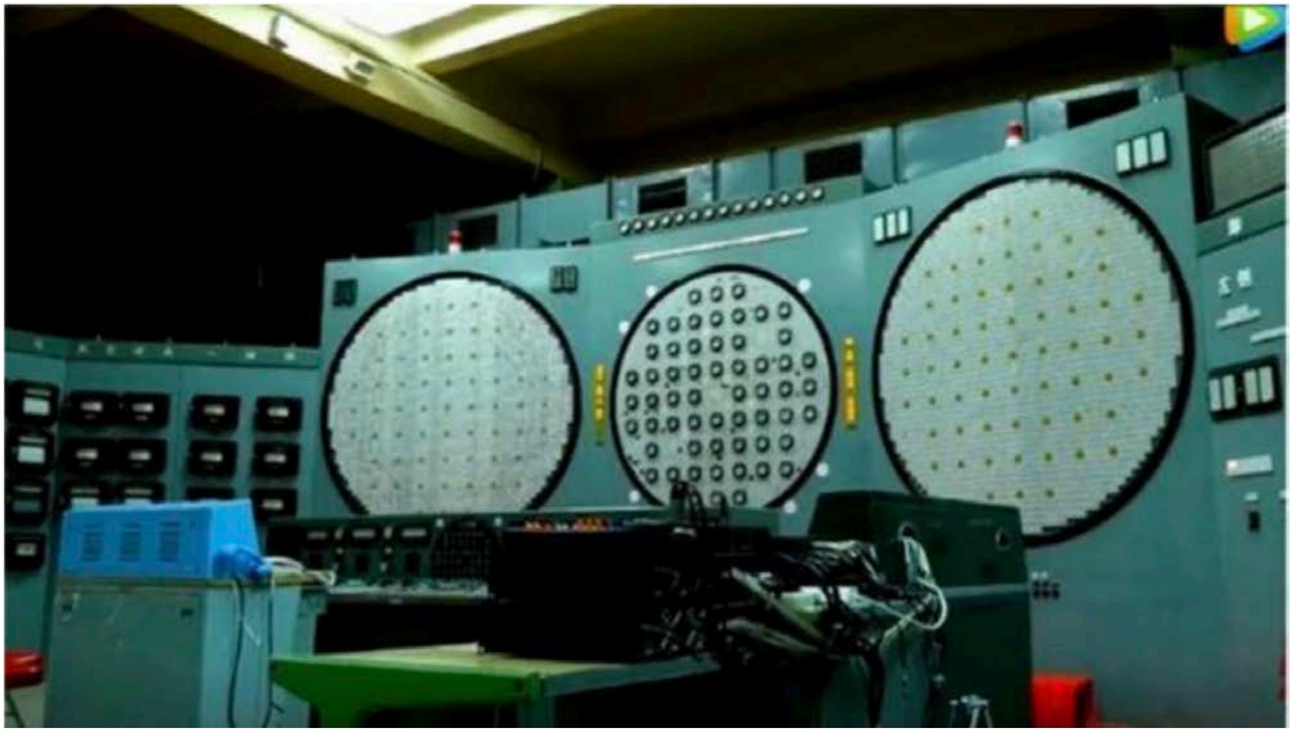

Figure 9. Screen capture of the reactor control room for the 404 Plant plutonium-production reactor, from the Chinese-language video, China Nuclear City 404.

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 7 January 1969.[20] 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 (**Figure 10**).

Figure 10. Screen capture of the heroic repair of a stuck fuel rod, from the Chinese-language video, *China Nuclear City 404.*

On 30 December 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. A new, increased goal was set for production, involving at least in part increased fuel burnup[††] and an increase in operating days from 288 to 324 days per year. 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% 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.[21]

Beginning in 1981, the period of the 6th Five-Year Plan (1981-1985, inclusive), was one in which additional uses were to be found for the reactor and dual-purpose technologies, especially for production of electrical power from the reactor. The *China Today* document, published in 1987, provides much less detail about plutonium production during this period, the account extending only 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, in 1983 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.

We note that there is no visual evidence today that the reactor ever provided electricity to the site. Indeed, the imagery indicates that there is a coal-fired power plant on-site. By 2017, well after the nuclear reactor had been shut down, we note that an apparently much larger coal-fired electrical generation capacity had been built at the site in another area near the reactor and reprocessing area (Figure 11).

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 8 November 1986, where it was declared that the reactor had completed its mission.[22]

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†† Increasing fuel burnup, measured in megawatt-days, increases the undesirable plutonium-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.

Figure 11. Expansion of the coal-fired electrical generation capacity at the 404 Plant site, in an area near the reactor and reprocessing area. One can see that the new cooling tower is much larger than the existing cooling towers in the area. The smaller cooling towers are comparable in size to the six cooling towers used by the reactor.

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:[23]

- 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‡‡ 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 burnup. Employing continuous piecewise-linear fits to Zhang's model, we calculated the yearly production as shown in **Figure 12**, which apparently agrees with **Figure 8** of Zhang's 2017 paper. In **Figure 13**, we sum up the yearly production to show cumulative WGPu production in the 404 Plant reactor, which totals up to about 2,000 kg.

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‡‡ The term capacity factor, as used by Zhang, and here as well, is the number of days the reactor operates per year divided by 365, the number of days in a year.

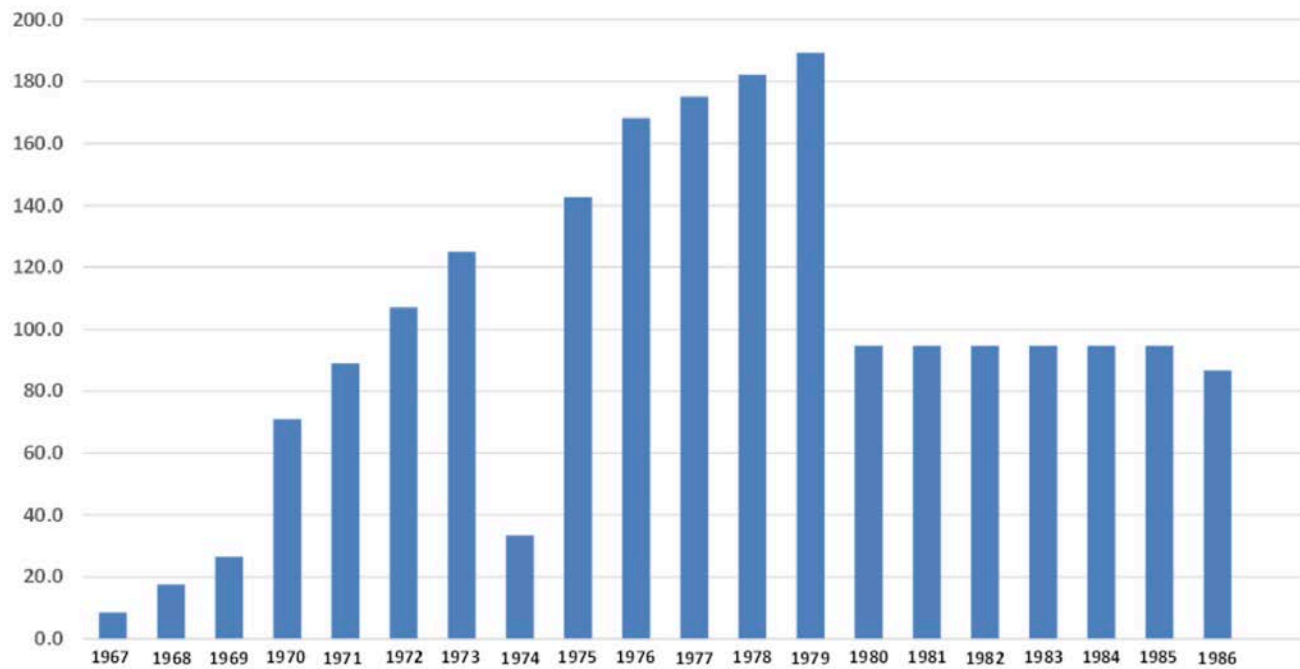

Figure 12. Yearly production of WGPu, in kilograms, in the 404 Plant reactor.

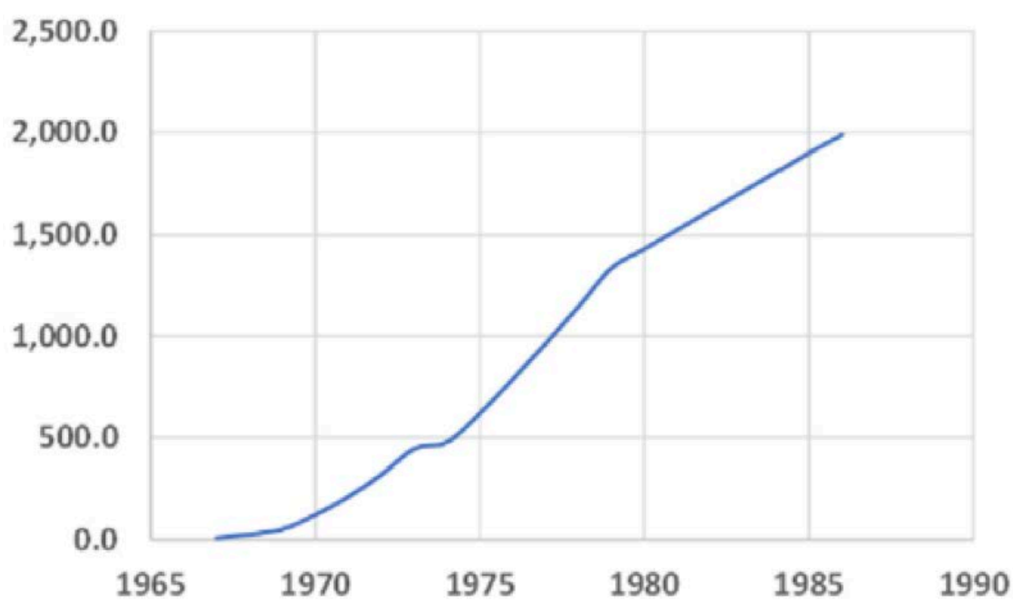

Figure 13. Cumulative WGPu production, in kilograms, in the 404 Plant reactor.

The 821 Plant

The 821 Plant was built in northern Sichuan Province (**Figure 14**) as part of the overall construction of Third Line facilities,[24] 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.[§§] Beginning of construction of the 821 Plant in October 1969 followed the February 1967 start of construction of the underground 816 Plant by some two and a half years.

Figure 14. Location of the 821 Plant and the adjacent residential area in Sanduizhen near the city of Guangyuan in northern Sichuan Province (straight-line distance from Guangyuan to the plant of 25 kilometers).

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. Shown in **Figure 15** and **Figure 16**, 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 as the crow files, although any path other than along the Bailongjiang crosses a number of deep ravines. 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.[25] We note the area adjacent to the reactor building designated for water treatment by Zhang.[26]

The production reactor was first started in December 1973, and stable, full-power operation was achieved on 11 October 1974.[27,28] As mentioned previously, based on a Chinese technical publication, we assess that full power was 600 MWt.[29] From there, the "1.3 reactor" target was reached in 1978, presumably production at a level thirty percent greater than that originally planned.

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§§ In Ref. 18, the reactor sites were designated as the "desert area [404], ravine area [821], and cave body [816]."

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."[30] The higher production was attributed to "deepening fuel consumption and strengthening power." Presumably, this meant increasing fuel burnup 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.[31]

Figure 15. The reactor and reprocessing areas of the 821 Plant.

Figure 16. Ground view of the 821 Plant reactor area.[32]

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 militarycommercial model.[33,34] In June 1982, the 816 Plant project was suspended, to be 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 while the reactors were still being designed.[35,36] 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.[37] A separate source recorded that military production at the factory was halted in 1988.[38]

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; that level was then 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 burnup, we calculated the yearly production of the 821 Plant according to Zhang's model as shown in **Figure 17**. In **Figure 18**, 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.

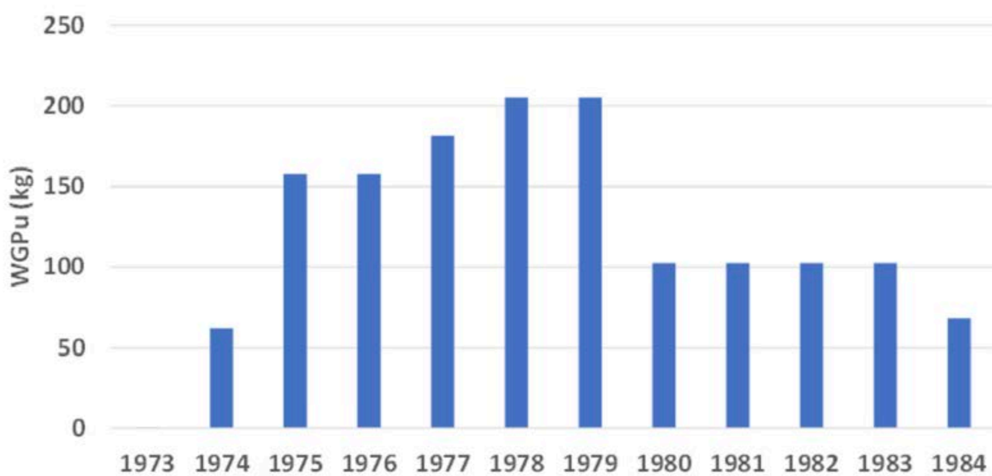

Figure 17. Yearly WGPu production at the 821 Plant reactor, from Zhang's model.

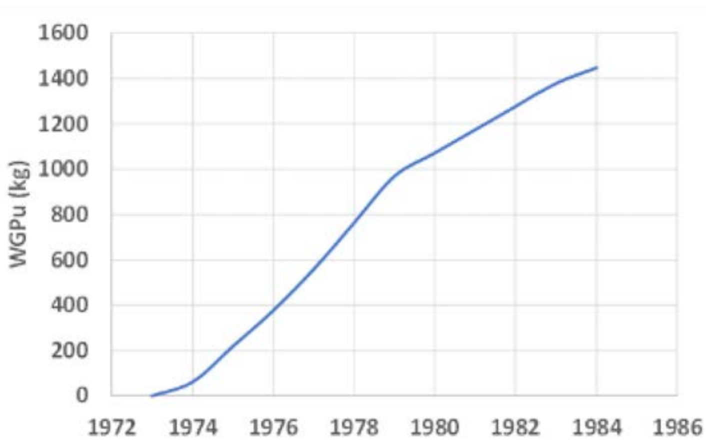

Figure 18. Cumulative WGPu production at the 821 Plant reactor, from Zhang's model.

REVIEW OF ESIN AND ANICHKINA'S ASSESSMENT

Esin and Anichkina produced an assessment that they compared to Zhang's 2011 assessment of WGPu production.[39] Zhang's 2011 assessment used a reactor power of 250 MWt for both the 404 and 821 Plant reactors (vs the 600 MWt used in his 2017 assessment and in this paper). 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 reator, Esin and Anichkina employed a reactor power of 500 MWt.[40] Esin and Anichkina also employed the same temporal profile for WGPu production in the 404 Plant reactor as Zhang (in 2011), which differs from that 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, vs 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 wrote they were informed that (1) the 821 Plant reactor had an operating power of 850 MWt, (2) it was capable of producing 280 kilograms of WGPu per year, and (3) by 1990, it could have produced up to 4.5 tons of WGPu. In addition, they 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 [use of italics is our emphasis].

The total value, to as much as 7,400 kilograms of WGPu produced in the 821 Project reactor, represents a dramatic increase over the 1,450 kilograms assessed by Zhang. We note the conditional nature of Esin and Anichkina's estimate. And we judge it possible that the operating power of the reactor could have been increased to 850 MWt, although 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 on several other grounds:

- At a production rate of 0.9 grams of WGPu per MWt-day of fuel burnup, even accepting an operating power of 850 WMt, 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 (the 404 Plant reactor reached 328 operating days per year), the production rate would have to be about 1.0 grams of WGPu per MWt-day of fuel burnup. This number is higher than the 0.8-0.9 grams per MWt-day from most production reactors,[41,42] although the French G1 production reactor approached it, with a reported production rate of 0.95 grams per MWt-day.[43]

- 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 would not have been the primary focus of reactor operation in that time period. On average, over the 19 years from 1990 to 2009, the reactor would have had to produce over 125 kilograms of WGPu per year. Even at 850 MWt, assuming 0.9 grams/MWt-day, the reactor would have had to devote an average of 163 days per year to WGPu production.

OUR REASSESSMENT OF CHINA'S WGPU PRODUCTION IN THE 404 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 a general shift in China's nuclear program in the early 1980s away from the purely military to a greater orientation on the commercial 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,[44] and (2) that military production at the factory was halted in 1988.[45] We acknowledge that neither of these claims is unambiguous about the date of the reactor shutdown, since the reactor may have been shut down earlier, while the reprocessing plant may have continued to reprocess spent fuel for WGPu until the latter dates. However, for comparison here, 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 that 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) would result in about 660 additional kilograms of WGPu, and a total of over 2,600 kilograms.

- For the 821 Plant reactor, we assume that it ran continuously to the end of 1987 at the peak 1979 production rate of 205 kilograms per year, resulting 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.

IMPLICATIONS OF THE DIFFERENT ASSESSMENTS

In Table 1, we summarize the three assessments of China's production of WGPu in the 404 and 821 Plant reactors. In summary of the discussion here, 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, we assume production proceeded at the 1979 peak value until shut down. In addition, we extend the closure date for the 821 Plant reactor from Zhang's inferred, but not confirmed, year of 1984, to our inferred year of 1987, when military production (arguably, at either the reactor or the reprocessing plant) was said to have ended.

Zhang (2017)	Our Reassessment	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. Assessments of China's production of WGPu at the 404 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:

- While Zhang relied on published Chinese sources and personal accounts from Chinese workers at the 821 Plant, Esin and Anichkina appeared to have drawn heavily on personal discussions with 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 employed a much higher reactor power of 850 MWt vs 600 MWt by Zhang. The lower value was given in Reference 18 of this paper, which was published in 1990 and discussed a 600-MWt reactor in terms that implicitly referred to all three reactors at the desert [404 Plant], ravine [821 Plant], and cave locations [the not-completed 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.

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

In our analysis, 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 nuclear devices that they would support. To perhaps span the numbers, we use two values for the amount of WGPu per weapon. At the upper end, we use the 6.4 kilograms of WGPu employed in the Fat Man bomb dropped on Nagasaki; at the lower end, we use the 4 kilograms of WGPu stated by Zhang[46] In **Table 2**, we show the numbers of nuclear devices that could be built in each case.

	Zhang's 2017 assessment (3,450 kg)	Our reassessment (5,200 kg)
6.4 kg per device (Fat Man)	540	810
4.0 kg per device (Zhang 2018)	860	1,300

Table 2. Numbers of nuclear devices that could be built with two different assessments of China's WGPu supply and two different amounts of WGPu per device.

APPENDIX: DESIGN POWER OF CHINA'S ORIGINAL PLUTONIUM PRODUCTION REACTORS

The *China Today* piece referenced repeatedly 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.[47]

The thermal design power is given in a 1990 technical publication as 600 MWt.[48] 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% 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 paper 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 project. To return to a point, it 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 further suggests that they have the same power.

Figure A1 and Figure A2 show the control panels for the 404[49] and 816[50] reactors (which was never completed), which visually are very similar, with the visually identical patterns on each core map.

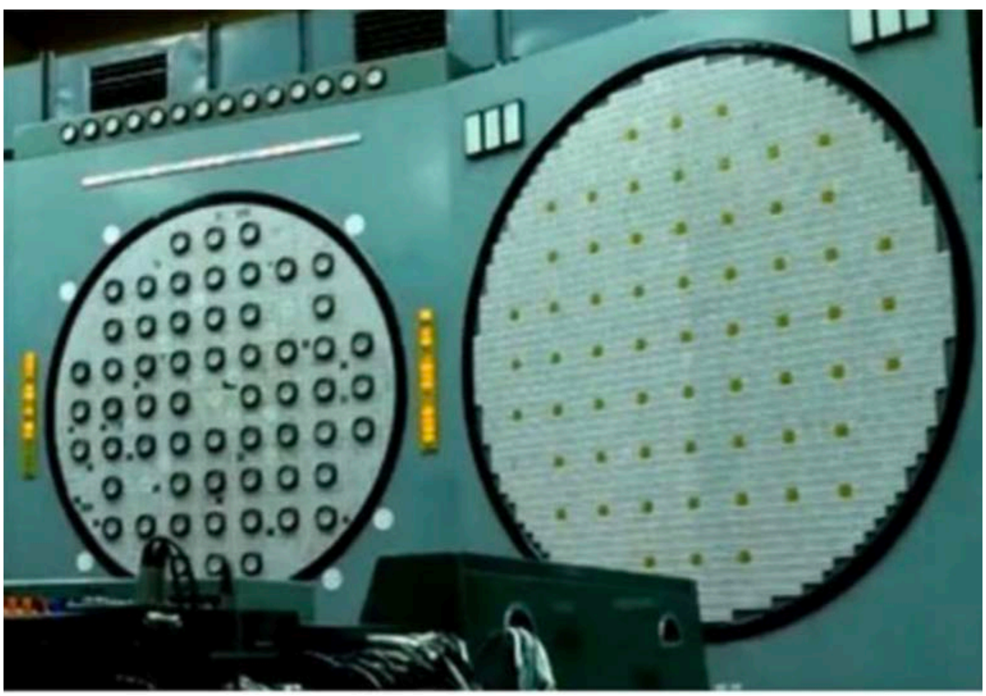

Figure A1. Control panels for the 404 Plant reactor, from the Chinese-language video, China *Nuclear City 404.*

Less conclusively, because it doesn't 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 project.[51]

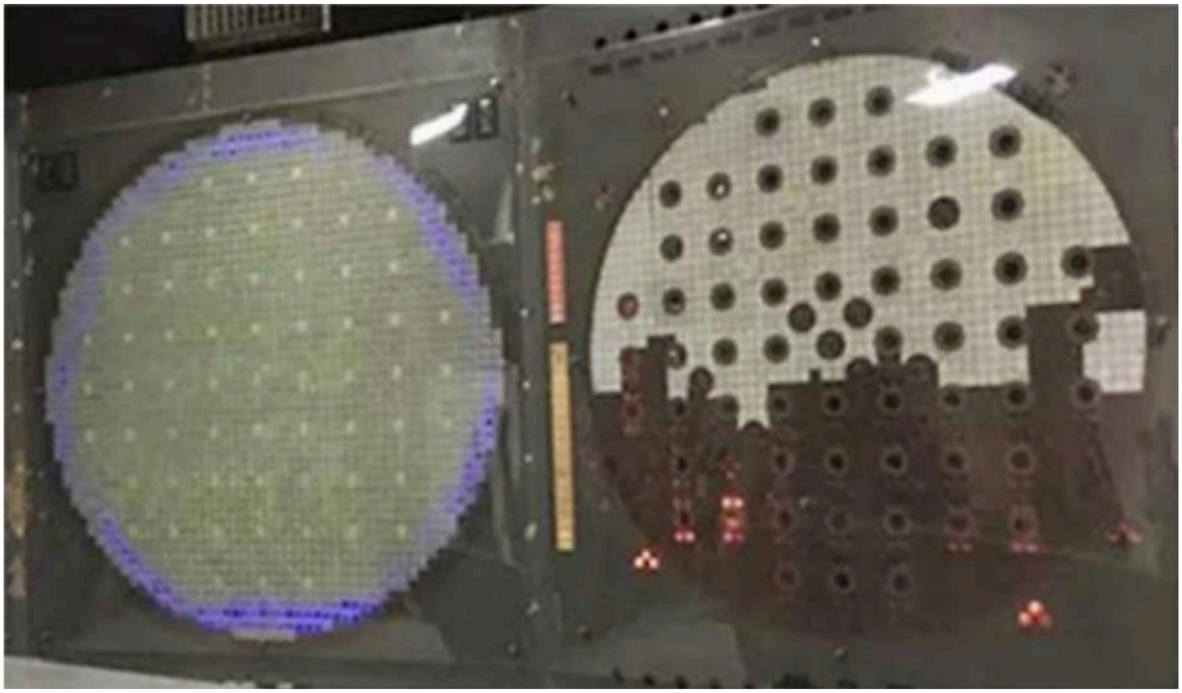

Figure A2. Control panels for the 816 Plant reactor, which was never completed. The underground plant site has recently been opened as a tourist site.

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.[52]

- 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 1.2 the design value.[53]

- Two other blogs stated that the 821 Plant reactor increased production to 1.3 times the original design value.[54,55]

- One of those blogs 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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