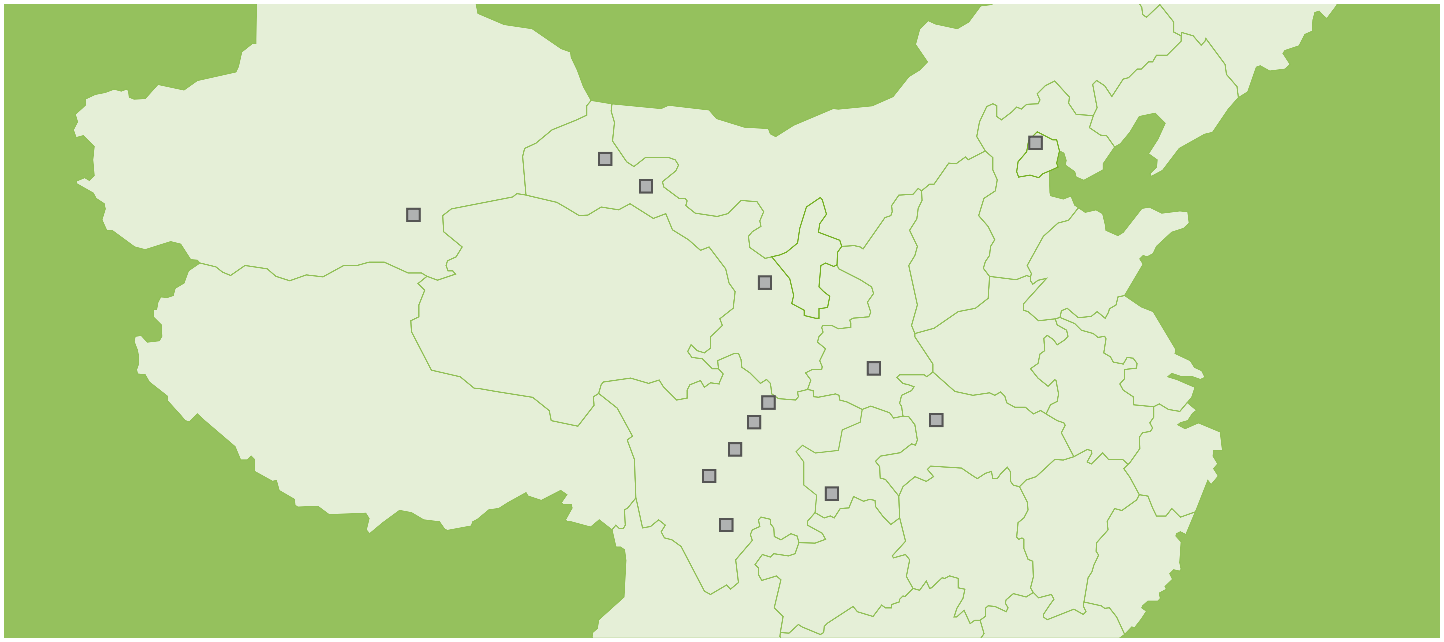

IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS

China's Fissile Material Production and Stockpile

Hui Zhang

Research Report No. 17
International Panel on Fissile Materials

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On the cover: The map shows fissile material production sites in China.

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About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from seventeen countries, including both nuclear weapon and non-nuclear weapon states.

The mission of the IPFM is to analyze the technical bases for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear disarmament, halting the proliferation of nuclear weapons, and ensuring that terrorists do not acquire nuclear weapons.

Both military and civilian stocks of fissile materials have to be addressed. The nuclear weapon states still have enough fissile materials in their weapon and naval fuel stockpiles for tens of thousands of nuclear weapons. On the civilian side, enough plutonium has been separated to make a similarly large number of weapons. Highly enriched uranium fuel is used in about one hundred research reactors. The total amount used for this purpose alone is sufficient to make hundreds of Hiroshima-type bombs, a design potentially within the capabilities of terrorist groups.

The Panel is co-chaired by Alexander Glaser and Zia Mian of Princeton University and Tatsujiro Suzuki of Nagasaki University. Its 30 members include nuclear experts from Brazil, China, France, Germany, India, Iran, Japan, South Korea, Norway, Pakistan, Russia, South Africa, Sweden, the United Kingdom, and the United States. Short biographies of the panel members can be found on the IPFM website, www.fissilematerials.org.

IPFM research and reports are shared with international organizations, national governments and nongovernmental groups. The reports are available on the IPFM website and through the IPFM blog, www.fissilematerials.org/blog.

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Overview

China began producing highly enriched uranium (HEU) and plutonium for nuclear weapons in the 1960s and is believed to have halted production the 1980s. Despite the passage of thirty years there has been no official policy declaration in this regard. This report uses newly available public information from Chinese sources to provide an improved reconstruction of the history of China's production of HEU and plutonium for nuclear weapons. This allows improved estimates of the amount of HEU and plutonium China has produced and of its current stockpiles.

HEU production and stockpiles

China started construction of the Lanzhou gaseous diffusion plant (GDP), also known as Plant 504, in 1958 with assistance from Soviet experts. Moscow, however, withdrew all its experts in August 1960 as relations between Beijing and Moscow were deteriorating, forcing China to become self-reliant. In January 1964, Lanzhou began to produce 90 percent enriched uranium (taken here as weapon-grade), which made possible China's first nuclear test, in October 1964. It appears that Lanzhou stopped HEU production for weapons in 1980 and shifted to making low enriched uranium (LEU) for civilian power reactors and possibly for naval reactors. It was shut down on 31 December 2000.

Construction of China's Heping GDP (Plant 814) began in 1966; the plant began operating in June 1970. It is believed to have ended HEU production for weapons purposes in 1987 and was turned to providing enriched uranium for naval reactors, research reactors, and power reactors. The Heping plant is still operating.

Plausible operating histories for these plants and estimates for China's consumption of HEU in nuclear tests and as reactor fuel suggest China's current inventory of weapon-grade HEU is about 14±3 metric tons, lower than previous estimates.*

Plutonium production and stockpiles

China produced plutonium for weapons at two nuclear complexes, Jiuquan (Plant 404) and Guangyuan (Plant 821). Each has a single production reactor. China also used its plutonium production reactors to produce tritium.

Construction of the Jiuquan plutonium-production reactor began in 1960. The reactor achieved criticality in October 1966 and reached its design power in mid-1975.

* All tons are metric tons in this report.

A great deal of effort went into increasing its plutonium-production rate, which rose 20 percent by 1979. During the 1980s, production decreased rapidly and the reactor was closed by November 1986. Decommissioning began after 1990.

In 1968, Beijing decided to quickly build a second plutonium-production complex at Guangyuan. Construction started in October 1969 and the reactor achieved criticality in December 1973. The plutonium production rate increased by 30 percent by 1978. The reactor was likely shut down in 1984. Decommissioning work began after 1990.

Taking into account the amount of plutonium consumed in nuclear tests and lost in reprocessing and fabrication, China's current inventory of plutonium for weapons is estimated to be about 2.9±0.6 tons, which is significantly larger than the previous estimate.

Introduction

China initiated its nuclear-weapon program in 1955 and began to construct its fissile-material-production facilities in the late 1950s with assistance from the Soviet Union. After Moscow withdrew all its experts in August 1960, however, China had to rely on its own efforts. HEU production began in 1964 and plutonium production in 1966.[1]

Given Beijing's concerns about the increasing tensions with the Soviet Union and the growing military presence of the United States in the region, China in 1964 began efforts to relocate its military- and heavy-industrial complexes to its southwestern and northwestern hinterland areas. These "third-line" projects were located so as to protect them from Soviet or American attack; the more vulnerable "first-line" sites were in China's border and coastal areas, and the "second-line" sites were in central areas. Chairman Mao Zedong considered the third-line construction campaign a key part of the national defense strategy for war preparation. The third-line projects were therefore required to be built quickly. The construction campaign stopped by the end of 1970s, however, when China adopted its economic reform and open-door policies.

In March 1964, the Second Ministry of Machine Building Industry began site selection for a new set of fissile-material-production facilities in the third-line area.[2] These facilities were required to be "near mountains, scattered and concealed."[3] The Heping GDP site was selected in November 1965, construction started in 1966.[4] The plant began operating in 1970.[5] To duplicate the Jiuquan plutonium-production complex, which became operational in 1966, Beijing decided in that same year to build another plutonium production facility (Plant 816) in caves under a mountain in Fuling district of Chongqing. Construction on the plant started in February 1967 but was halted in the early 1980s. The plant was never completed.[6]

Given the very slow progress of Plant 816, Beijing in 1968 decided to quickly build another plutonium-production complex (Plant 821) to meet the urgent need for a backup of the Jiuquan complex. Construction started on the Guangyuan reactor (Reactor 821) in 1969 and the reactor went into operation in 1973.[7] China also decided in 1969 to build a third-line uranium-enrichment plant in Hanzhong, Shaanxi (Plant 405)[8] but this plant did not start operations until the 1990s, and it used imported Russian centrifuges for civilian purposes. In addition, in 1970, China initiated Project 827, which possibly included a tritium-production reactor and a power reactor built inside caves. That project was terminated in the early 1980s without being completed.

The "military-to-civilian conversion" policy and nuclear-material-production facilities

In December 1978, the Third Plenary Session of the 11th Central Committee of the Chinese Communist Party adopted a policy of economic reform and an open-door policy for trade. Accordingly, China shifted its focus from military to economic development, based on Deng Xiaoping's judgment of "no large world wars within the next twenty years" which replaced Mao's "war preparation" strategy.

In April 1979, the Second Ministry proposed that the nuclear industry focus on military-to-civilian conversion.[9] After 1981, the central government reduced investment in construction of nuclear infrastructure and decreased its production of HEU and plutonium.[10] China's nuclear enterprise had to find its own way to survive.

The Second Ministry was reorganized and renamed the Ministry of Nuclear Industry (MNI) in 1982 – and then further reorganized and renamed the China National Nuclear Corporation (CNNC) in 1988. In August 1982, the MNI and the Commission for Science, Technology and Industry for National Defense proposed the guiding principles for the nuclear industry. These principles, which the central government approved in November 1982, included:

- Assuring that military needs were met. Instead of quantity of production, China's nuclear industry was directed to focus on further improvement in technology, increased quality of nuclear products, and improved weapons performance;
- Rationalizing nuclear-infrastructure construction and uranium-mining projects. This resulted in the suspension and finally termination of these projects, and the separation of plutonium and production of HEU for weapons; and
- Improving management, administration, and economic efficiency.

Meanwhile, the government began to increase investments in the civilian nuclear sector.

Figure 1. Enrichment and reprocessing facilities in China. While China has not declared officially that it has ended HEU and plutonium production for weapons, it appears that China shut down its plutonium-production reactors by November 1986 and stopped reprocessing around 1987. It also ended HEU production for weapons in 1987 and since then has produced LEU for naval and power reactors and small amounts of HEU for research reactors. This history is summarized in Table 1.

Facility	Start-up	Shutdown	Initial and final capacity
Uranium enrichment plants			Separative Work Units (SWU) per year
Lanzhou GDP	1964	HEU production ended 1980; LEU production until shutdown in 2000	0.1–0.25 million SWU/year
Heping GDP	1970	HEU production for weapons ended in 1987; since then other uses	0.11–0.23 million SWU/year
Plutonium production reactors			Kg of plutonium per year
Jiuquan reactor	1966	Before November 1986	158–190 kg/year
Guangyuan reactor	1973	1984 (estimated)	158–205 kg/year
Reprocessing plants			
Jiuquan intermediate pilot plant	1968	Early 1970s	60 kg/year
Jiuquan reprocessing plant	1970	~1987	Assumed to match production reactor
Guangyuan reprocessing plant	1976	~1987	Assumed to match production reactor

Table 1. History and estimated capacity of China's facilities for producing fissile material for weapons.

HEU production and inventory

China has produced HEU for weapons at two complexes, the Lanzhou GDP (Plant 504) and the Heping GDP (Plant 814 at Jinkouhe). China also used these GDPs to produce HEU for its research reactors and LEU for its naval reactors. The Lanzhou GDP, which began HEU production in January 1964 and switched to LEU production around 1980, was closed in December 2000 and replaced by a civilian centrifuge enrichment plant after 2001.[11] The Heping GDP, a third-line facility, began operating in 1970.[12] It stopped producing HEU for weapons in 1987. Since then, it continues operating, presumably enriching uranium for non-weapon military uses, and possibly for civilian uses, i.e., in a dual use mode.[13]

In addition to the Heping GDP, Plant 814 is also operating a pilot centrifuge enrichment plant near Emeishan, located about 3.6 miles from a larger commercial centrifuge plant near that city. This plant is likely enriching for non-weapon military uses and possibly civilian uses.[14]

Currently, China operates a total of three civilian centrifuge enrichment plants at Hanzhong in Shaanxi province (Plant 405), Lanzhou in Gansu province (Plant 504), and Emeishan in Sichuan province (Plant 814) to produce LEU. The commercial SWU-production capability as of the end of 2016 was estimated to be around 5.4 million SWU/year.[15]

Lanzhou Gaseous Diffusion Plant

China initiated its nuclear-weapon program in 1955 with expectations of assistance from the Soviet Union. A Chinese delegation went to Moscow in April 1956 to negotiate Soviet assistance on establishing China's nuclear industry.[16] An enrichment plant was not requested initially because it would need a huge investment and consume a great deal of electricity. China therefore decided to pursue the plutonium route to weapons first.

During the talks, however, the Chinese delegation realized that an uranium-enrichment plant was imperative in order to have a complete nuclear fuel cycle.[17] The Chinese representatives also recalled references to a small American plant with a capacity to produce about 5 kg of HEU per day (around 0.35 million SWU/year) costing about $500 million, that they thought would be affordable to China. The Chinese delegation therefore requested an enrichment plant as well. The Soviet delegation was at first surprised. After two days, however, it agreed to supply China with GDP equipment that just had been retired but was reusable with some modest repair.[18] The Chinese delegation immediately obtained approval from Beijing. On 17 August 1956, the two capitals signed a formal agreement on Soviet assistance to the Chinese nuclear program, including the GDP.

China's financial crisis in 1956 led Beijing to reopen the question of whether to keep the enrichment plant, or ask Moscow to enrich China's natural uranium, or even postpone the HEU route. Finally, in March 1957, China decided to keep a domestic enrichment plant in its plan in order to have a complete nuclear fuel cycle and independent nuclear force. The size of the plant was reduced significantly.[19]

A site for the GDP was chosen in September 1957 beside the Yellow River near Lanzhou in Gansu province. The site had previously been planned for an aircraft-production plant. In October 1957, the Second Ministry approved the design.[20] Construction began in spring 1958 with help from the Soviet Union. In May 1958, Moscow informed Beijing that it would deliver 13 batches of diffusers between September 1958 and 1959. This would require the cascade hall and the auxiliary projects to be ready for installation of those diffusers before the end of 1959.[21]

Nuclear cooperation between China and the Soviet Union began to break down in June 1959, when Moscow refused to provide a model atomic bomb and other technical documents. In late 1959, therefore, the leadership of the Second Ministry requested a speedup of the construction of the GDP in order to learn as much as possible from the Soviet experts before they left. On 18 December 1959, the construction of main processing building was finished, and on 27 December, the first group of diffusers was installed. In August 1960, however, while the plant was still incomplete, Moscow withdrew all its experts.[22] China was left to move forward on its own with the HEU production program.

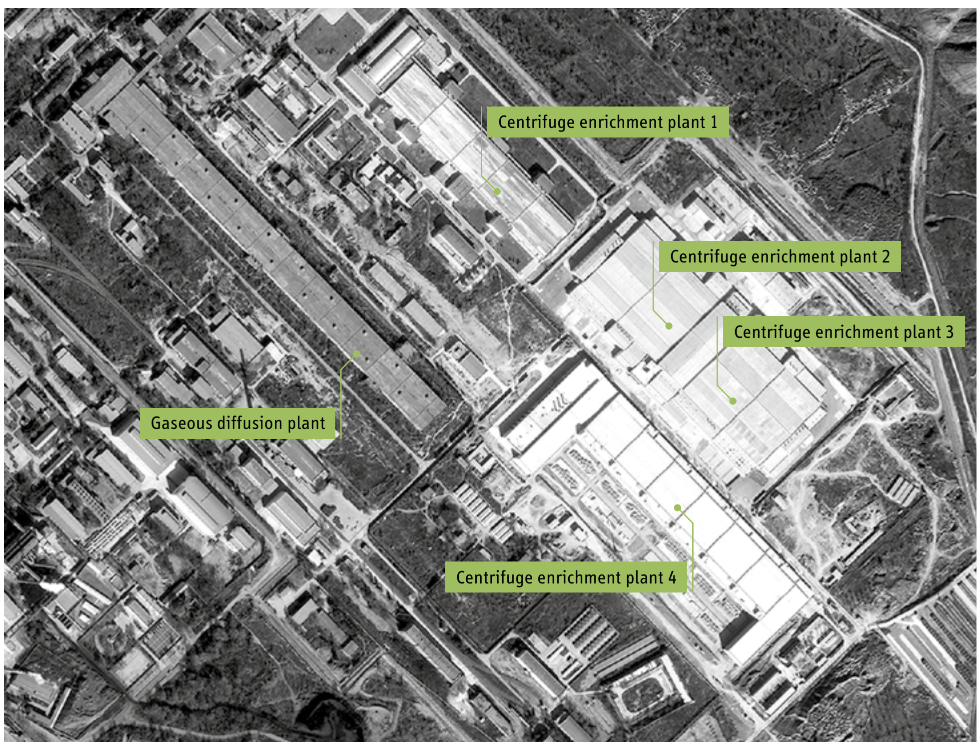

Figure 2.1. Lanzhou uranium enrichment plant. Satellite image from 18 January 2015 (coordinates 36°08'53.30'' N/103°31'24.49'' E). Credit: DigitalGlobe. The GDP was closed on 31 December 2000. The first Lanzhou centrifuge enrichment plant, CEP1 (0.5 million SWU/year) was commissioned in 2001; Lanzhou CEP2 (about 0.5 million SWU/year) (officially, Lanzhou Centrifuge Commercial Demonstration Project) in 2010; and Lanzhou CEP 3 (a commercial centrifuge facility with a capacity of about 0.5 million SWU/year) in 2012. The first phase of Lanzhou Centrifuge Project 4 (about 1.1 million SWU/year) started in 2016.

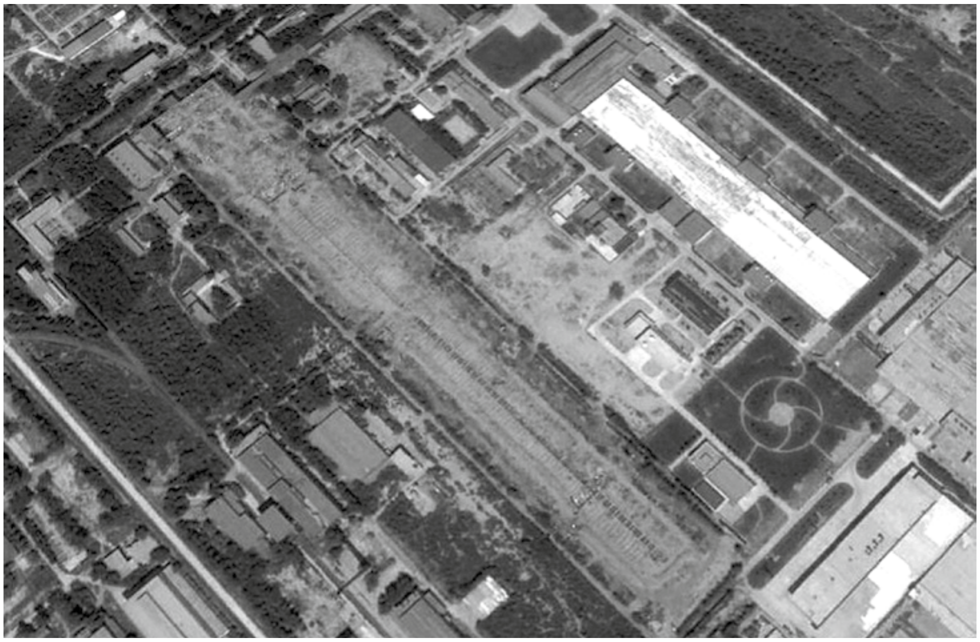

Figure 2.2. Site of the former Lanzhou gaseous diffusion uranium enrichment plant. The facility was demolished in mid-2017. The satellite image is from 14 August 2017. Credit: Google Earth.

The construction of the enrichment plant was much further advanced than China's first plutonium-production reactor, which had just started civil-engineering construction in March 1959. The Second Ministry therefore decided to suspend the construction of the reactor and make the Lanzhou GDP its top priority. By November 1962, the assembly and installation of all the cascades were complete.[23]

China also needed to produce its own uranium hexafluoride (UF_6). Given that Moscow refused in June 1960 to provide the production technology for UF_6, the Second Ministry decided to build a pilot production facility at the China Institute of Atomic Energy (CIAE) in a suburb of Beijing.[24] A simplified approach for producing UF_6 was designed that produced about 3.4 kg of product from a test line in October 1960. The pilot facility – which had only two simple stoves, each 2 meters high and less than half a meter in diameter – produced a total of 18.5 tons of UF_6 by October 1963.[25] This was the first feed for the Lanzhou GDP. Meanwhile, construction began on a large UF_6 conversion plant in April 1960 at the Jiuquan plant. After several trials the large plant was commissioned in November 1963. It delivered its first batch of UF_6 product to Lanzhou in February 1964.[26]

The Lanzhou plant started up its first group of cascades in April 1963 and, on 14 January 1964, the GDP began to produce 90-percent-enriched uranium.[27] Meanwhile, in December 1962, the central government gave its approval for China's first nuclear bomb test in 1964.[28] To meet this deadline, the Lanzhou plant completed start-up of all its cascades and went into full operation in July 1964.[29] The first HEU weapon core was fabricated in May 1964 at a workshop in the Jiuquan plant, with a second core (as a backup) soon after.[30] China's first nuclear test was conducted on 16 October 1964.[31]

HEU production

No available Chinese publications reveal the production capacity of the Lanzhou plant for its early years. In 1971, Manhattan Project physicist, Ralph Lapp, estimated that at start-up the Lanzhou plant might have produced about 136 kg/year of weapon-grade HEU, based on the experience of the U.S. Oak Ridge GDP.[32] Production of 90-percent-enriched HEU at this rate would be equivalent to an enrichment capacity of 23,000 SWU/year at a tails assay of 0.4 percent, or 26,000 SWU/year with 0.3 percent tails.

Lapp speculated that the Lanzhou GDP would have been able to double its annual production by 1966 as its operators gained experience. In 1972, the U.S. Defense Intelligence Agency estimated that Lanzhou was producing 150–330 kg/year of HEU.[33] This production rate is equivalent to 26,000–56,000 SWU/year at a tails assay of 0.4 percent, or 29,000–64,000 SWU/year for 0.3 percent tails.

China Today reported that the plant reached its original design capacity by mid-1975.[34] This capacity is estimated to be 100,000 SWU/year.[35]

In August 1975, the "Program for Increased Output of Primary Products during the Fifth Five-Year Plan," which covered the period 1976–1980, was proposed for the diffusion plant. Beginning in 1975, the plant increased its separation capacity through improvement of separation membranes, raising production capacity by 26 percent.[36] By 1978, cascade flow rates had increased by 35–47 percent.[37]

After China adopted a policy of economic reform in 1978, it pursued a program of military-to-civilian conversion of its nuclear facilities. On 7 October 1979, the Second Ministry submitted to the central government a request to export enriched uranium to other countries and received immediate approval from Deng Xaioping.[38] In 1981, China began to supply LEU for the international market. This suggests that in 1980 Lanzhou likely stopped HEU production and shifted to producing LEU for civilian power reactors or naval reactors or both.[39]

During the Sixth Five-Year Plan (1981–1985), the GDP increased its production capacity further by optimizing cascade arrangements and using separation membranes with higher separation efficiency, corrosion and vibration resistance, and longer lives.[40] The Lanzhou enrichment plant reported that the capacity was double the original design capacity by 1984. This was described as "one plant becomes two plants."[41]

After 1985, the Lanzhou GDP continued to increase its enrichment capacity, in part by installing higher-performance diffusers. Eventually, the capacity increased to 0.25 million SWU/year, 2.5 times of its original design capacity.[42] The facility was permanently closed on 31 December 2000.[43] During 2001 and 2002, the facility was cleaned up and prepared for decommissioning. Since then, it has been kept in a status described as "sealed and maintenance."[44] Demolition of the facility began in mid-2017 and appears to have been completed in August 2017.

Based on the above information, the history of the Lanzhou GDP capacity is shown in Figure 3.[45] Operating continuously at full capacity through 1979, after which HEU production ended, it could have produced 1.2 million SWU, sufficient to produce about 6.4 tons of 90 percent-enriched HEU (assuming a tails assay of 0.3 percent).

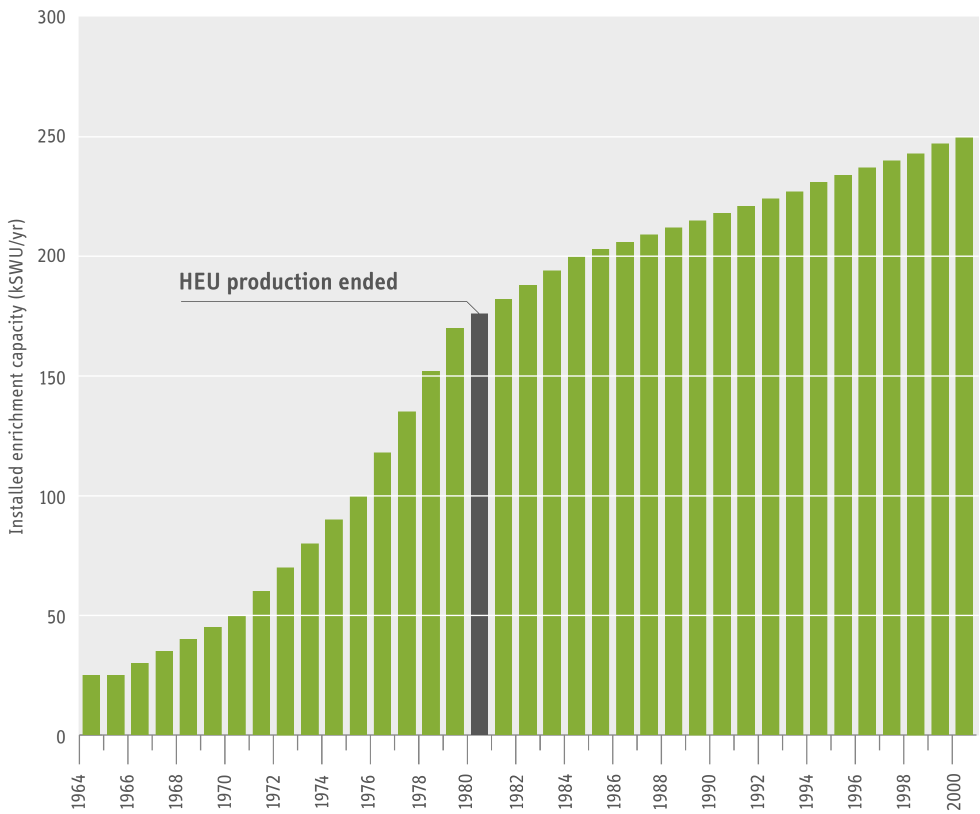

Figure 3. History of operating capacity of the Lanzhou plant from 1964 to 2000 (thousands of SWU/year). The plant reached its original design capacity, estimated as 100,000 SWU/year, by mid-1975. It stopped HEU production in 1980 and shifted to producing LEU. The design capacity was doubled by 1984, and eventually increased to 2.5 times its original design capacity. It was shut down in 2000.

In 1996, China and Russia agreed to build an enrichment plant at the Lanzhou site using Russian centrifuges. The plant is sited next to the GDP and began operations in July 2001 with a capacity of 0.5 million SWU/year.[46] It produces only LEU for non-weapon purposes.

In July 2010, at the same site, a second centrifuge plant, Lanzhou Centrifuge Project 2 (officially known as the Lanzhou Centrifuge Commercial Demonstration Project) was commissioned.[47] This plant, which is equipped with Chinese made centrifuges, had a capacity of about 0.5 million SWU/year. Lanzhou Centrifuge Project 3, with a capacity of about 0.5 million SWU/year, was commissioned in December 2012, and Lanzhou Centrifuge Project 4 with a capacity of about 1.1 million SWU/year in 2016.[48] In total, the current centrifuge capacity at Lanzhou is about 2.6 million SWU/year, or about 10 times that of the shut-down GDP.

Heping Gaseous Diffusion Plant

In November 1965, the site for a second uranium enrichment plant was selected on the bank of the Dadu river in the Heping Yizu area of the Jinkouhe district of the city of Leshan in Sichuan province. The Heping site was chosen because it is flat, surrounded by mountains with access to water for cooling.[49] (Gaseous diffusion plants are very energy intensive.)

The Heping GDP (Figure 4) was constructed in two stages: 1966–1968 and 1969–1972.[50] The first unit began operating in June 1970.[51] It may initially have produced only LEU.

In about 1975, the Heping GDP reached its original design capacity of 110,000 SWU/year.[52] In 1972, the United States Defense Intelligence Agency estimated that this plant could produce 750–2,950 kg of weapon-grade uranium per year, which would correspond to about 145,000–569,000 SWU/year at a tails assay of 0.3 percent.[53]

Like the Lanzhou plant, the Heping facility expanded its capacity during the Fifth Five-Year Plan. By 1980, the last year covered by that plan, it had increased its production capacity to 1.5 times its original design capacity (described by officials as "one plant becomes one and half plant").[54] This suggests Heping might have achieved a capacity of about 0.16 million SWU/year.[55]

Figure 4. Heping gaseous diffusion plant (Plant 814) at Jinkouhe. Satellite image from 28 September 2013 (coordinates 29°13'58.49 N, 103°03'49.95 E). Credit: DigitalGlobe. Located next to the Dadu river, the Heping plant appears to have two enrichment buildings.

Although Beijing did not publicly declare a cutoff, based on available information, it is assumed the Heping plant ended its HEU production for weapon purposes in 1987.[56] Since 1987, it is believed that the plant has produced LEU for naval reactors and power reactors and possibly HEU for research reactors. Some Chinese media reported that the plant would close in 2003.[57] It survived, however, and its production capacity was increased by almost half, to 0.23 million SWU/year, by 2004.[58]

Since 2007, the Heping plant also has operated a small pilot centrifuge plant with a capacity of 0.25 million SWU/year near Emeishan – presumably to produce enriched-uranium products for non-weapon military uses and possibly also for civilian use.[59] Around 2013, a larger commercial centrifuge plant with a capacity of around 0.8 million SWU/year began operation near Emeishan.[60]

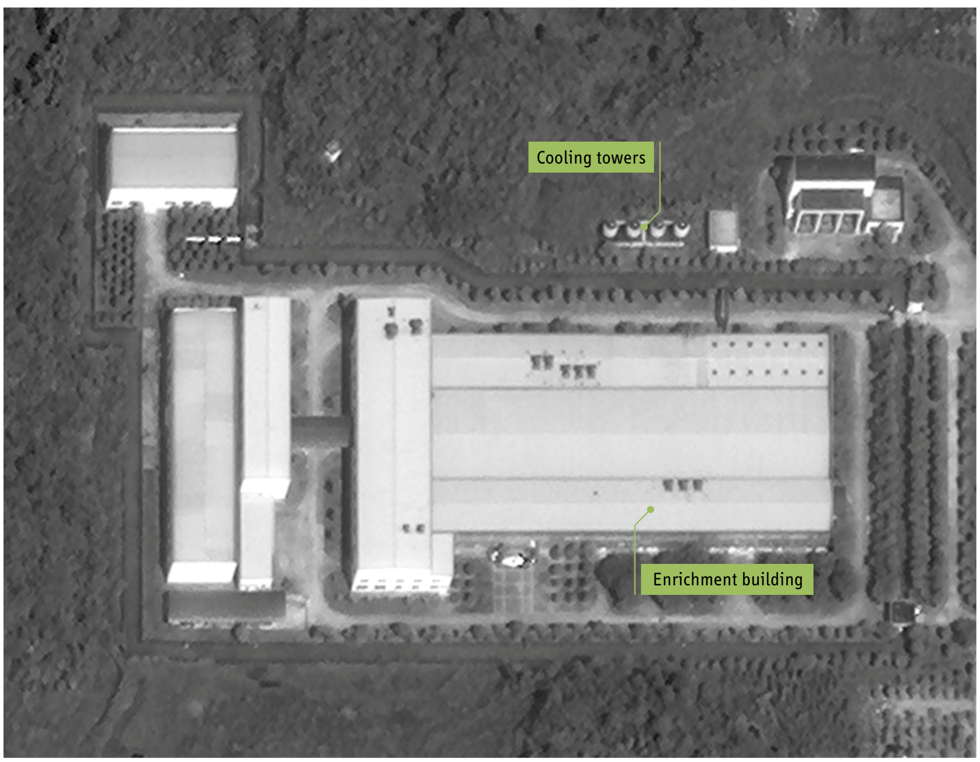

Figure 5. The pilot centrifuge plant near Emeishan city. Satellite image from 5 October 2014 (coordinates 29°38’38.70”N/103°29’25.12” E). Credit: DigitalGlobe.

The history of the Heping GDP's estimated enrichment capacity is shown in Figure 6.[61] Operating continuously at full capacity up to 1987, the Heping GDP would have produced 2.2 million SWU, sufficient to produce about 11.2 tons of weapon-grade HEU (assuming a tails assay of 0.3 percent).

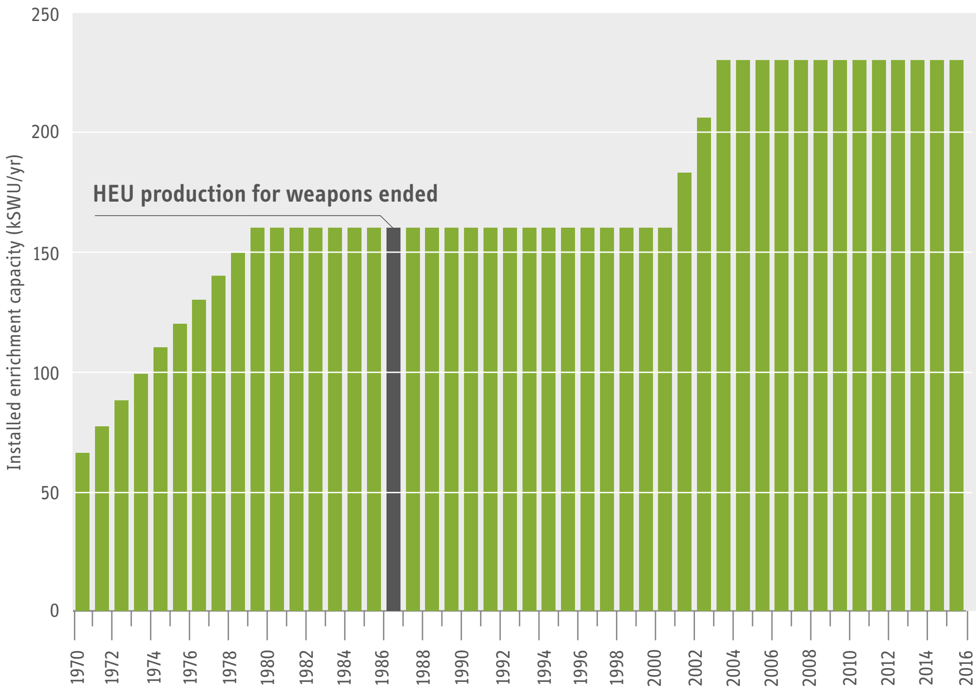

Figure 6. Operating history of the Heping enrichment plant from 1970 to 2016 (thousands of SWU/year). The plant reached its original design capacity of 110,000 SWU/year in 1975 and increased it to 1.5 times that level by 1980. It is believed the plant ended HEU production for weapons in 1987. Since then, it has operated to produce LEU for naval reactors and power reactors and possibly a small amount of HEU for research reactors. Plant capacity was increased by another 45 percent to 230,000 SWU/year between 2001 and 2004. It continues to operate today. The graph shows the production level at the end of each respective year.

Other demands for uranium enrichment prior to 1987

Along with HEU production for weapons, which ended in 1987, China's two enrichment plants also would have supplied enriched uranium for research and naval reactors.

Enrichment of uranium recovered from irradiated fuel. China had a limited amount of high-quality uranium ore and reportedly began in 1970 to use as feed for HEU production uranium recovered from the irradiated fuel discharged from its plutonium-production reactors.[62] As a result, China could have used roughly 0.2 million more SWU than would be required to produce the same amount of HEU from natural uranium.[63]

Research reactor fuel. China has operated a number of HEU-fueled research reactors, most of which have been converted to LEU-fueled reactors or closed (see Table 2). The two highest-power research reactors that once used HEU fuel are the High Flux Engineering and Test Reactor (HFETR), which has a capacity of 125 megawatts thermal (MWt), and the 5 MWt Min Jiang Test Reactor (MJTR). Both were converted to LEU in 2007. In addition, since 1970, China has operated a Zero-Power Fast Neutron Critical Assembly, which has a core of 50 kg of 90 percent uranium-235. It was built at the CIAE near Beijing. In 1971, as a third-line facility, it was moved to the Nuclear Power Institute of China (NPIC) in Chengdu and in 1986 back to the CIAE again.[64] As of 2015, this assembly was reported to be in long-term shutdown status.[65]

The pre-1987 requirements of enrichment work for research reactor fuels (estimated as no more than 0.1 million SWU) would be a few percent of the total enrichment work that was available to make HEU.[66]

Currently, China operates only a few reactors that need HEU fuel, and future HEU use in its research reactors will not be significant. The China Experimental Fast Reactor (CEFR, 65 MWt), which reached criticality in July 2010, started up with an initial core of about 240 kg of 64.4 percent enriched uranium provided by Russia and has operated infrequently and perhaps at low power. The CIAE expects to load the CEFR with plutonium-uranium mixed-oxide (MOX) fuel before 2020.

China's remaining major operational HEU-fueled research reactors include one Miniature Neutron Source Reactor (MNSR) at Shenzhen University (approximately 1 kg of 90 percent U-235), which is being converted, and a Pilot Reprocessing Plant Nuclear Criticality Safety Experiment Facility. China has not released any information about its stock of HEU for these reactors but could have produced a large stock since 1987 if it wanted to do so, given that the Heping GDP and the pilot CEP of Plant 814, both assumed to be for dual use, could each produce more than 1 ton of 90 percent enriched HEU per year.

Reactor	Operator	Characteristics (before conversion)	Status
China Experimental Fast Reactor	China Institute of Atomic Energy, Beijing	240 kg 64.4% HEU supplied by Russia 65 MWt/25 megawatts electric (MWe)	Operational since December 2010
DF-VI Fast Neutron Criticality Facility	China Institute of Atomic Energy, Beijing	50 kg 90% HEU 0.05 kWt	Long-term shutdown
Pilot Reprocessing Plant Nuclear Criticality Safety Experiment Facility	China Institute of Atomic Energy, Beijing	89.37% HEU, critical mass 1.6 kg U-235 0 kWt	Operational since 2000
Miniature Neutron Source Reactor (MNSR-SZ)	Shenzhen University, Guangdong	1 kg 90% HEU 30 kWt	Operational since 1988, being converted to LEU
Miniature Neutron Source Reactor (MNSR-IAE)	China Institute of Atomic Energy, Beijing	1 kg 90% HEU 27 kWt	Operational since 1984, converted March 2016 to 12.5% LEU
Miniature Reactor Zero Power Facility	China Institute of Atomic Energy, Beijing	1 kg 90% HEU 0 kWt	Operational since 1984; converted to LEU?
High Flux Engineering and Test Reactor	Nuclear Power Institute of China , Chengdu, Sichuan	90% HEU 125 MWt; converted to 19.75% LEU	Converted in 2007, operational
Min Jiang Test Reactor	Nuclear Power Institute of China, Chengdu	fueled by HFETR spent fuels; 5 MWt	Converted in 2007, operational
Miniature Neutron Source Reactor MNSR-SD	Research Institute of Geological Science, Jinan, Shandong	1 kg 90% HEU 30 kWt	Closed in 2008
Miniature Neutron Source Reactor MNSR-SH	Shanghai Institute for Measurement and Testing Technology	1 kg 90% HEU 30 kWt	Closed in 2006
HFETR Critical Assembly	Nuclear Power Institute of China, Chengdu	90% HEU 0 kWt	Converted in 2007, long-term shutdown

Table 2. China's major research reactors that used HEU.[67]

Naval reactor fuel. China launched its nuclear-powered-submarine program in 1958. To keep these submarines from competing with the nuclear-weapon program for HEU, China decided to fuel them with LEU.[68] This fuel was probably less than 5 percent enriched.[69] A land-based prototype reactor began tests in May 1970 and became fully operational in July 1970. The full-life test of its reactor core ended in December 1979 and the spent fuel was discharged in 1981.[70]

China's first Type 091 Han-class nuclear-powered attack submarine (SSN) entered service in 1974 and was retired in 2000. Its first Type 092 Xia-class nuclear-powered strategic ballistic-missile submarine (SSBN) was launched in 1982. China began to deploy its second-generation SSN (Type 093 Shang-class) in 2006, and the second-generation SSBN (Type 094 Jin-class) in 2014.[71] It has been reported that China currently has nine nuclear submarines, including five SSNs and four SSBNs.[72]

To estimate China's HEU stocks for weapons, it is necessary to subtract the enrichment work required for naval-reactor fuel before 1987. Given that the Lanzhou GDP stopped HEU production for weapons in 1980 and subsequently produced LEU for naval reactors or civilian power reactors, it is necessary to estimate the SWU used for naval fuel before 1980.

It is estimated that the Lanzhou and/or Heping would have produced LEU for about 10 naval reactor cores before 1980 to meet the demand for one core for the land-based prototype reactor, five cores for the Han-class submarines, one core for the Xia-class SSBN, and a few spares.[73] Each of these submarines has one 110 MWt pressurized-water reactor (PWR).[74]

If the reactor cores are designed to have lifetimes of 10 years, it is estimated that each fuel load of China's naval reactors would require about 2.8 tons of 5 percent LEU.[75] Thus, LEU production for 10 naval reactor cores would reduce the SWU available for making HEU for weapons by about 200,000 SWU at a tails assay of 0.3 percent.[76]

Thus China's two gaseous diffusion plants would have supplied roughly 500,000 SWU to enrich uranium for non-weapon purposes (see Table 3). This would have left an estimated 2.9 million SWU available for producing HEU for weapons, sufficient for about 15 tons of weapon-grade HEU.

Finally, it should be noted that China's new generation of naval reactors is likely to still use LEU fuel. Some Chinese accounts mention that the NPIC, which is part of CNNC and is mainly responsible for designing naval reactors, developed a second-generation naval reactor in 2006.[77] This is consistent with an authoritative statement that the project on the development and engineering of the new generation of naval reactor was officially approved by 2005.[78] That time frame is also consistent with the delivery of the first second-generation nuclear submarine to the navy in 2006.

Reportedly, CNNC's small ACP100 reactor is based on new naval-reactor technology.[79] CNNC started work on the ACP100 in 2010 as a key project of the 12th Five-Year Plan. The ACP100 reactor is a small, multi-purpose, modular PWR with a passive safety system. In 2014, CNNC completed its preliminary design and, in April 2016, the design passed an International Atomic Energy Agency general safety review.[80] The ACP100 reactor is described as a 310 MWt (100 MWe) small modular PWR, with the core and cooling system integrated inside the pressure vessel. The reactor has a 60-year design life. It is refueled every two years and uses 4.2 percent enriched LEU fuel.[81]

One NPIC expert stated in 2011 that the ACP100 development program would adopt mature technology, including fuel assemblies, steam generators, control-rod drive mechanisms, and main pumps mastered by NPIC.[82] This suggests that China's new generation of naval reactors may still use LEU fuel.

If China operates 10 naval reactors, and each reactor requires about 2.8 tons of 5 percent LEU for a lifetime of 10 years, it would need 0.02 million SWU/year of enrichment work. If the fleet of naval reactors is increased tenfold, it would need an enrichment capacity of 0.2 million SWU/year. The Heping GDP, with its capacity of 0.23 million SWU/year and the pilot CEP, which has a capacity of 0.25 million SWU/year are each large enough to meet the needs.

In the past, it was thought that China might have used HEU to fuel a tritium-production reactor.[83] Newly available information shows, however, that China produced tritium for boosting the power of the fission primaries of its nuclear weapons mainly at its natural-uranium-fueled Jiuquan plutonium-production reactor until it was closed in the 1980s.[84]

It is not clear how China has produced tritium since it closed its plutonium-production reactors. In 1970, China started Project 827, which included a heavy-water-moderated tritium-production reactor, but the project stopped in the early 1980s and was never completed. If China extracts tritium from the moderator of its two Candu heavy-water reactors (728 MWe each), it could produce annually about 260 grams of tritium,[85] which would be sufficient to supply China's current nuclear arsenal.[86]

Consumption and losses of HEU produced for weapons

Some of the HEU produced for weapons was consumed in nuclear-weapon tests or went into waste as process losses.

China has carried out 45 nuclear-weapon tests.[87] These may have consumed about 750 kg of HEU or the equivalent of 0.15 million SWU.[88] Some HEU was lost as the material was processed; about 90 kg of weapon-grade uranium, or the equivalent of 0.02 million SWU, would have been lost if China's process losses were about 0.5 percent, similar to those in the United States.[89]

In addition, A.Q. Khan, the former head of Pakistan's HEU program, claims that China provided 50 kg of weapon-grade HEU to Pakistan in 1982.[90] Many Chinese experts doubt this.

Military inventory of HEU

It is estimated that China could have a current inventory of about 14±3 tons of HEU for weapons.[91] This new estimate is somewhat lower than the 2010 IPFM estimates and significantly lower than other recent estimates.[92] The assumed 20 percent uncertainty is due mainly to the range of possible tails assays. There is no official information about tails assays in China's gaseous diffusion enrichment program.

Activity	Million SWUs produced or consumed
Enrichment work prior to 1987	**3.38**
Enrichment of irradiated uranium	**-0.2**
Enrichment work used for non-weapon purposes	
Research-reactor fuel	**-0.1**
Naval-reactor fuel	**-0.2**
Other removals	
Process losses	**-0.02**
Nuclear tests	**-0.15**
Possible transfer to Pakistan	**-0.01**
Total remaining available for weapons HEU	**2.7**

Table 3. China's estimated uranium enrichment work until the end of HEU production for weapons.

Plutonium production and inventory

China has produced plutonium for weapons at two sites:

1. Jiuquan Atomic Energy Complex (Plant 404) in Jiuquan, Gansu province. This site includes China's first plutonium-production reactor and associated reprocessing facilities.
2. Guangyuan plutonium-production complex (Plant 821), located at Guangyuan in Sichuan province. This third-line site also included a plutonium-production reactor and reprocessing facilities.

In the past, the original design power of the Jiuquan and Guangyan reactors was each assumed to be about 250 MWt.[93] Authoritative publications that have recently become available, however, state that each Chinese plutonium-production reactor had a design power of 600 MWt.[94]

Production of plutonium for weapons has ended at both sites. Since 1983, however, China has maintained a closed-fuel-cycle policy and is interested in separating plutonium from the spent fuel of civilian power-reactors.[95] In December 2010, it began testing a pilot civilian reprocessing plant with a capacity of 50 tons of spent fuel per year at the Jiuquan complex. Since then, however, the plant has been shut down most of the time because of technical problems. As of December 2015, according to China's declaration to the IAEA, it had separated 25.4 kilograms of plutonium.[96]

In early 2015, the government approved the construction of a 200 ton/year demonstration reprocessing plant at Jinta in Gansu province; CNNC started site preparation for the project that July. CNNC also has been negotiating with France's Areva over the purchase of a commercial reprocessing plant with a capacity to reprocess 800 tons of spent fuel per year.

Jiuquan complex

In January 1958, Jiuquan, in the Gobi Desert, was selected as the site for China's first plutonium-production complex. The Jiuquan plutonium-production reactor (Reactor 801) is a natural-uranium-fueled, graphite-moderated, water-cooled reactor.[97] In April 1958, Soviet experts began preliminary design. Construction began in March 1960. Just after the concrete baseplate was poured in August 1960, however, the Soviet Union withdrew its experts. At the time, China had not received the key reactor components.[98] Beijing therefore decided to suspend construction of the reactor and concentrate on completing the Lanzhou enrichment plant.

In June 1962, the Second Ministry approved resumption of construction of the Jiuquan reactor and, in February 1965, the central government approved a speedup of the project to meet the needs of the hydrogen-bomb development program. Installation of the graphite core structure began in the spring of 1966, and the reactor went critical in October 1966. In December 1967, the reactor achieved 0.5 percent of design power.[99] After that, it increased power only gradually while upgrading equipment, finally reaching its design power only in mid-1975.[100]

During the early years of operation, accidents occurred frequently, accounting for the reactor operating below design power.[101] In January 1969, a serious accident caused overheating and the meltdown of an aluminum channel liner and the fuel elements in it. It took more than 20 hours for workers to deal with the problem under high-radiation conditions. Incidents that led to damaged fuel elements and aluminum channel liners were frequent for some time, often requiring shutdown of the reactor to discharge irradiated fuel rods and change channel liners and the graphite tubes outside them.

After 1970, with improvements, the reactor achieved continuous operation, with no need for stopping for fuel loadings and discharges or for changing channel liners or graphite tubes.[102] The reactor ran without an unscheduled shutdown until it went out of service in early 1974 for tests, repair, and maintenance.[103]

In October 1972, the water tank that supported the weight of the entire reactor core was discovered to be leaking. A year later, in September 1973, the central government approved the shutdown of the reactor for repair and maintenance. The reactor shut down on 30 December 1973 for equipment repair and inspection. It took 103 days to resolve the leak problem.[104] After this work, reactor operation entered a long stable period, with the reactor reaching its design power of 600 MWt for the first time in mid-1975.[105]

In 1976, the Second Ministry established an increased production output goal in the Fifth Five-Year Plan (1976–1980).[106] The reactor's power was raised through improvements in the cooling system; the fuel burnup was increased; and reactor-days of operation increased from 288 to 324 days per year.[107] As a result of these measures, by 1979, plutonium production had increased by 20 percent, realizing the "1.2 reactor" goal set in the Fifth Five-Year Plan a year ahead of schedule.[108]

After adopting its policy of military-to-civilian conversion in 1981, the central government reduced its requirements for the production of nuclear materials for weapons.[109] Plutonium production at Jiuquan decreased rapidly thereafter.[110] In 1982, the Ministry of Nuclear Industry (MNI) confirmed the technical feasibility of converting plutonium-production reactors to the dual mission of producing electric power as well as plutonium.[111]

China Today reported the conversion work started in September 1984, but it did not specify if this meant the Jiuquan reactor, the Guangyan reactor, or both.[112] The Jiuquan reactor was designed for dual use from the beginning, but was not set up to generate electricity from the beginning.[113] It appears the Jiuquan reactor never operated in a dual-use mode.[114] It was closed down by November 1986.[115]

In August 1987, at a State Council meeting chaired by then-vice premier Li Peng, it was decided officially to "close the reactor and stop reprocessing" (Ting dui ting hua) and "maintain the plant as a base for civilian reprocessing."[116] After exploring various options during the late 1980s and 1990s, a pilot civilian reprocessing plant was built in the 2000s at the Jiuquan plant.[117]

Decommissioning of the reactor began after 1990. By 2000, the first stage, including the removal of internal structures of the cooling towers, had been completed.[118]

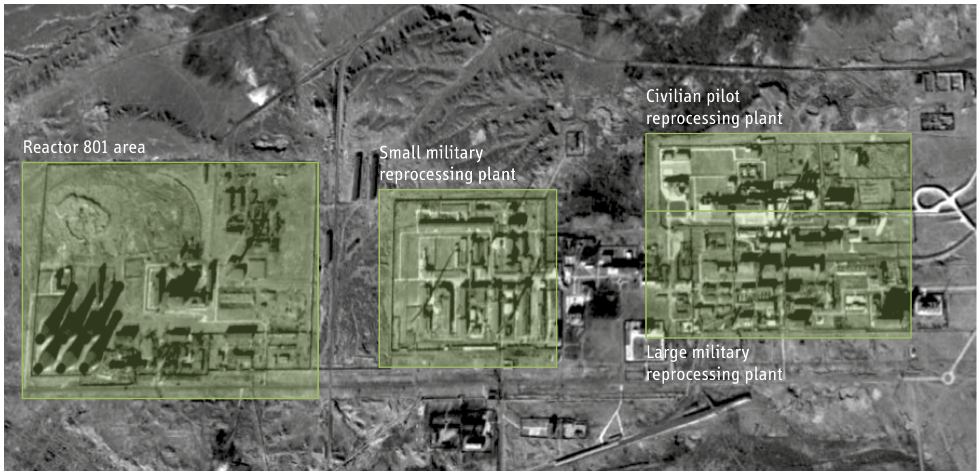

Figure 7. Jiuquan plutonium complex. Satellite image from 31 December 2012 (coordinates 40° 13’ 50.20”N/97° 21’ 49.41”). Credit: DigitalGlobe and Google Earth.

Reprocessing plants. China began to develop a military reprocessing capability in 1956 with assistance from the Soviet Union, based initially on the Soviet reprocessing technology, which involved the precipitation of sodium uranyl acetate. In 1958, the Chinese government selected a reprocessing site at the Jiuquan complex.

After the USSR stopped providing aid in 1960, China began to re-evaluate the Soviet technology. In 1962, Beijing decided to build a small pilot plant (also known as the Small Plant) first and then a large military reprocessing plant (also known as the Large Plant). In 1964, China finally decided to give up the Soviet approach and use the U.S. PUREX technology in the plants.

Construction of the pilot plant began in 1965, and it began operation in September 1968. It had two production lines that could together process 0.4 tons of irradiated uranium per day and operate for more than 250 days per year.[119] This meant that the plant could separate about 60 kg of weapon-grade plutonium per year.[120] It separated the plutonium for China’s first plutonium-based weapon test, conducted in December 1968.[121] It ended operations when the larger plant, also built near the reactor site, began operating in April 1970.

The large plant and the small plant were developed in parallel because of the tense international security environment in early 1960. In May 1964, Beijing decided to use the PUREX technology for the large plant and in July 1965, approved a proposal to build the plant within the Jiuquan complex. Construction of the large plant started in April 1966. Because of the Cultural Revolution, completion of the plant was delayed until early 1970, putting it more than one year behind schedule. The large plant started plutonium-separation operations in April 1970.[122] It probably stopped around 1987.[123]

Power of the reactor. The thermal power of the reactor is a key factor in determining its plutonium-production rate. For the Jiuquan reactor, a design power of 600 MWt – or even an increase by 20 percent to 720 MWt – is within the upper bound of the 840 MWt estimate based on the size of the Jiuquan reactor's six cooling towers. On the basis of commercial satellite images, it appears that the Jiuquan reactor towers have a top diameter of about 30 meters, which suggests a design power for each tower of 14–140 MW.[124]

The design of the Jiuquan reactor is likely to be similar to that of the EI-2 reactor at the Siberian Chemical Combine in Seversk (formerly Tomsk-7) near Tomsk. The EI-2 reactor, the first dual-purpose reactor constructed in the Soviet Union, started operation in September 1958 – several months after Soviet experts began the preliminary design of the Jiuquan production reactor in April 1958. The EI-2 reactor had a design power of 400 MWt (and an electricity-generating capacity of 100 MWe), later upgraded to 1,200 MWt. It also used cooling towers.[125]

The new information that the two Chinese plutonium-production reactors had the same design power is consistent with the facts that the Jiuquan and Guangyuan reactors were described as "2.5 reactors" by the end of 1970s after the Jiuquan reactor and Guangyuan reactor became "1.2" and "1.3" reactors, respectively (which indicated that the two had the same original design power). Also, new information describes the graphite stack of Reactor 816 (see following discussion) as having 2,001 fuel channels,[126] the same number as the I-1 and EI-2 reactors at Tomsk-7.[127] In practice, Plant 816 was the first dual-use (plutonium- and electricity-production) reactor in China.[128]

A number of authoritative Chinese publications state that the Jiuquan reactor reached its design power by the first half of 1975, and the Guangyuan reactor in October 1974. Later, during the Fifth Five-Year plan (1976–1980), both reactors increased their power and realized the goal of together becoming "2.5 reactors."

Plutonium production. The estimated cumulative plutonium production by the Jiuquan reactor is based on the above information and the following assumptions:

- 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.[129] The capacity factor during 1967–69 is assumed to be 40 percent, and the capacity factor during 1970–73 is assumed to be 80 percent (288 days per year);
- The reactor was shut down for 103 days during 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; and
- From 1980 until shutdown in November 1986, the plutonium-production rate was about half of that in 1979.[130]

With these assumptions, the Jiuquan reactor produced an estimated total of 2,200 gigawatt-days (GWd) of fission heat and generated a total of about 2 tons of weapon-grade plutonium.[131]

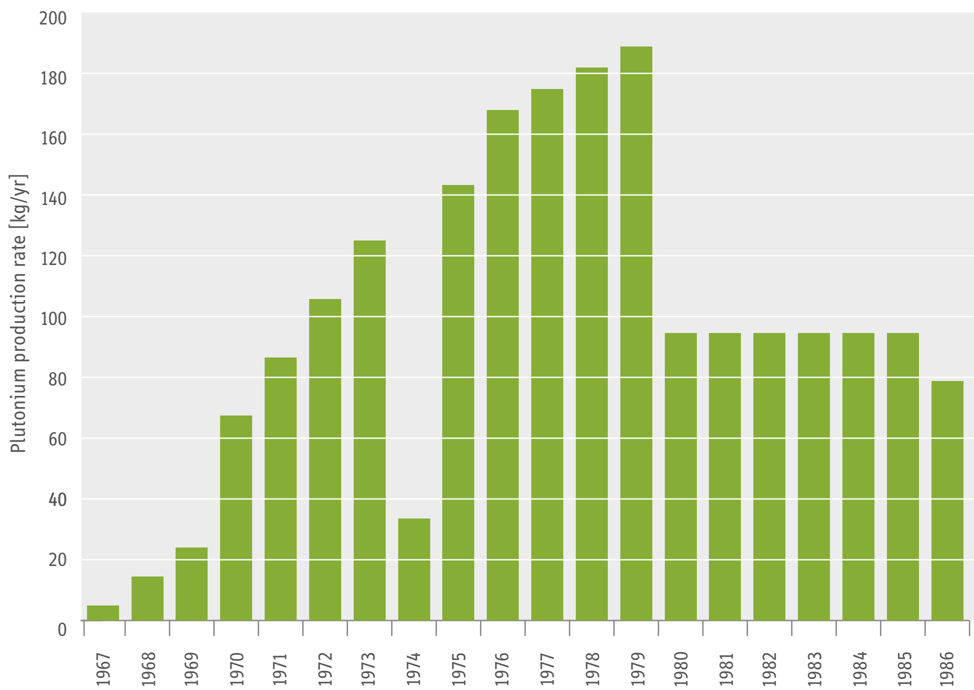

Figure 8. Reconstructed history of production of weapon-grade plutonium by the Jiuquan reactor (kg/year). The reactor reached its design power of 600 MWt in mid-1975. The plutonium-production rate was increased by 20 percent by 1979. Under the military-to-civilian conversion policy, the reactor reduced plutonium production in the 1980s and was shut down by November 1986.

Guangyuan Complex

Beijing decided in 1966 to build a duplicate of the Jiuquan complex in caves under a mountain as a third-line project (Plant 816). Construction started in February 1967. However, the extremely hard rock made the work of mining out the caverns very slow, and the project was expected to take a long time to complete. With border conflicts with the Soviet Union increasing in the late 1960s, and the occupation of Czechoslovakia by Soviet troops in August 1968, Beijing decided to rush the building of an alternative third-line plutonium production complex. Mao Zedong reportedly said that "we have to go even by riding a donkey if there is no road, and take my royalties if there is no money."[132]

In October 1968, the Second Ministry started site selection in Guangyuan in Sichuan province. In February 1969, the central government approved Project 821.[133] After a fierce border conflict with the Soviet Union in March 1969 – the Chen-pao Island event – Beijing became seriously concerned about the possibility that Moscow might conduct “surgical strikes” against China’s nuclear facilities.[134] In May 1969, Premier Zhou Enlai approved the issuing of a “Joint Notice to Rush Construction of Project 821.” In August 1969, a joint design team began work at Guangyuan, and construction started on 10 October 1969.

It is reported that Lin Biao, then Vice Chairman of the Central Committee of the Communist Party of China, proposed in July 1969 to move the Jiuquan reactor to Sichuan. The scientists of the plant argued that to move the reactor would be to destroy it. Zhou ordered that the plant not be moved but rather that its production be increased.[135]

In November 1969, Beijing decided to divide the employees of the Jiuquan reactor into three groups. While a small group remained at the plant to continue production, the largest group relocated to the Guangyuan site, and the third went to the underground Plant 816.

The Guangyuan reactor achieved criticality in December 1973 and its design power by October 1974.[136] It took only 10 months to achieve full design power because its operators had learned from the Jiuquan reactor. Also, the Guangyuan reactor had a simple once-through cooling system, which drew cooling water from the nearby Bailongjiang River and discharged heated water downstream.

During 1973–1976, the operators mainly focused on instrumentation, including sensors for monitoring the flow and temperature of the water coolant, computer controls, and the large cooling-water intake pump.[137]

Like the Jiuquan reactor, the Guangyuan reactor was a natural-uranium-fueled, graphite-moderated, water-cooled reactor with a design thermal power of 600 MWt and an electrical generating capacity of 100 MWe.[138] However, it should be noted that, while the reactor was designed for dual use purposes, no turbogenerator or steam generator were installed initially. It was converted in 1984.

In 1976, the Second Ministry ordered the two reactors to increase plutonium production and reach a combined output of “2.5 reactors” during the Fifth Five-Year Plan.[139] By increasing the power and U-235 burnup, the Guangyuan reactor increased its plutonium-production rate by 30 percent by 1978, leading to it being dubbed the “1.3 reactor.”[140] Together with Jiuquan’s “1.2 reactor,” the two reactors became “2.5 reactors” by the end of 1970s.[141]

Newly available information suggests that, as part of the policy of military-to-civilian conversion, the Guangyuan reactor likely started work to move to the dual mission of plutonium and electric-power production in September 1984.[142] Some say that the conversion was completed in 1986, but because of safety concerns after the Chernobyl disaster, the reactor never operated.[143] The reactor was likely closed in 1986.[144]

It has been reported that in August 1987, the central government made a strategic decision at the important Beidaihe meeting on the Guangyuan plant of “ending military production and converting to civilian use.”[145] With parallel actions at the Jiuquan complex, it appears that China officially ended its plutonium production for weapons in 1987.[146]

After the shutdown of the reactor, the Guangyuan plant began to shift to a primarily civilian mission, including aluminum manufacture. The new enterprise was called the CNNC Sichuan Wuzhou Industry Company.[147] The second volume of the history of Plant 821 (covering the years 1988–2006) discusses the plant’s transition to civilian activities. During 1990 – 2000, the plant also carried out the early stages of decommissioning of its reprocessing plant. After 2006, Plant 821 was renamed the CNNC Sichuan Environmental Protection Engineering Co., Ltd., which focuses on the decommissioning of nuclear facilities and management of nuclear waste.[148]

The reprocessing plant at the complex started operation in 1976, reaching its design capacity in 1977.[149] It was presumably closed in 1987.

Figure 9.1. Satellite image overview of the Guangyuan plutonium-production complex. This image was taken on 31 October 2015 (coordinates: 32° 29’ 44.27” N /105° 35’ 24.48” E). Credit: DigitalGlobe and Google Earth.

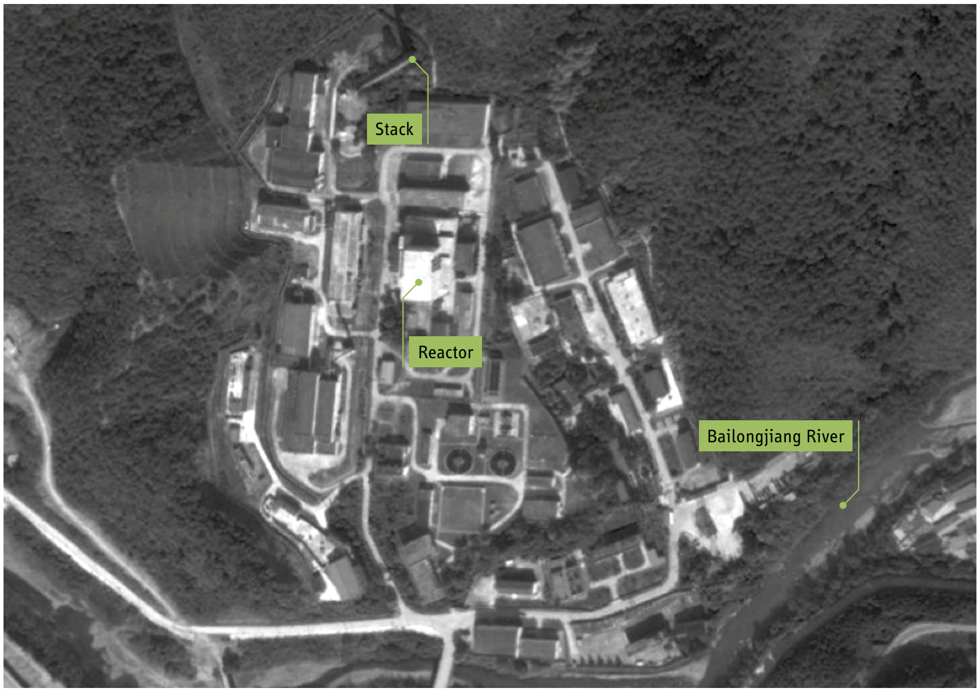

Figure 9.2. The reactor 821 area. This image was taken on 31 October 2015 by a DigitalGlobe satellite. Credit: DigitalGlobe and Google Earth.

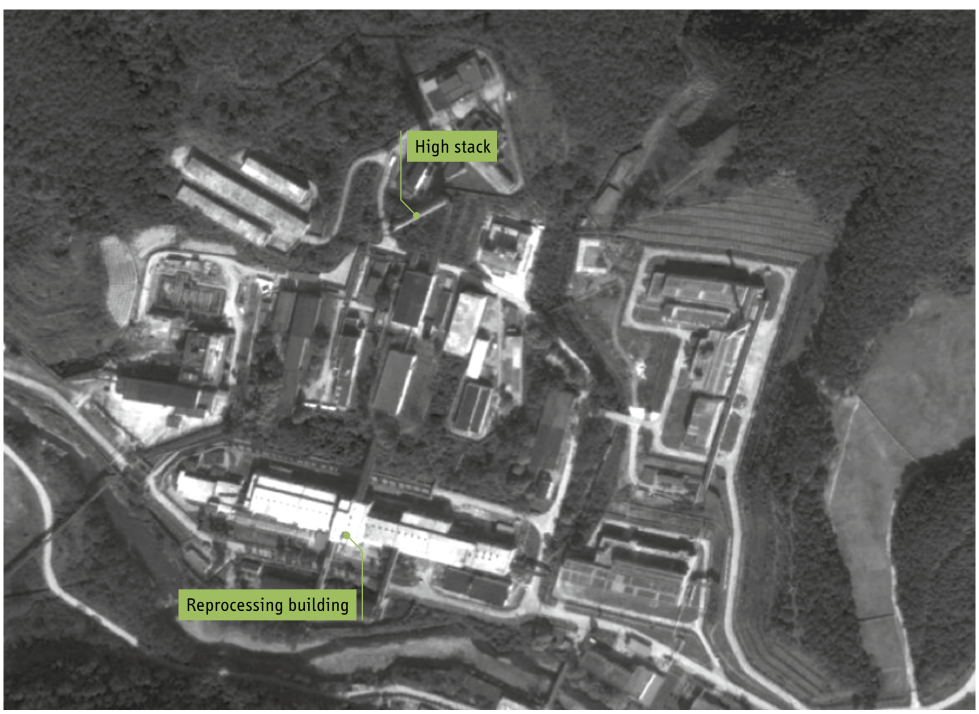

Figure 9.3. The area of reprocessing plant. This image was taken on 31 October 2015 by a DigitalGlobe satellite. Credit: DigitalGlobe and Google Earth.

Plutonium production. Cumulative plutonium production by the Guangyuan reactor is estimated on the following assumptions:

- From December 1973 to October 1974, the reactor power increased to a design power of 600 MWt with a capacity factor of 40 percent;[150]
- From November 1974 to December 1976, the reactor power maintained a design power of 600 MWt with a capacity factor of 80 percent;
- From January 1977 to December 1978, the plutonium-production rate increased linearly by 30 percent and maintained that level until December 1979;
- From 1980 until shutdown for conversion in August 1984, the plutonium-production rate was reduced by about half from that in 1979.[151]

Under these assumptions, the Guangyuan reactor could have produced a total of about 1,600 GWd of fission energy and generated a total of 1.4 tons of weapon-grade plutonium.

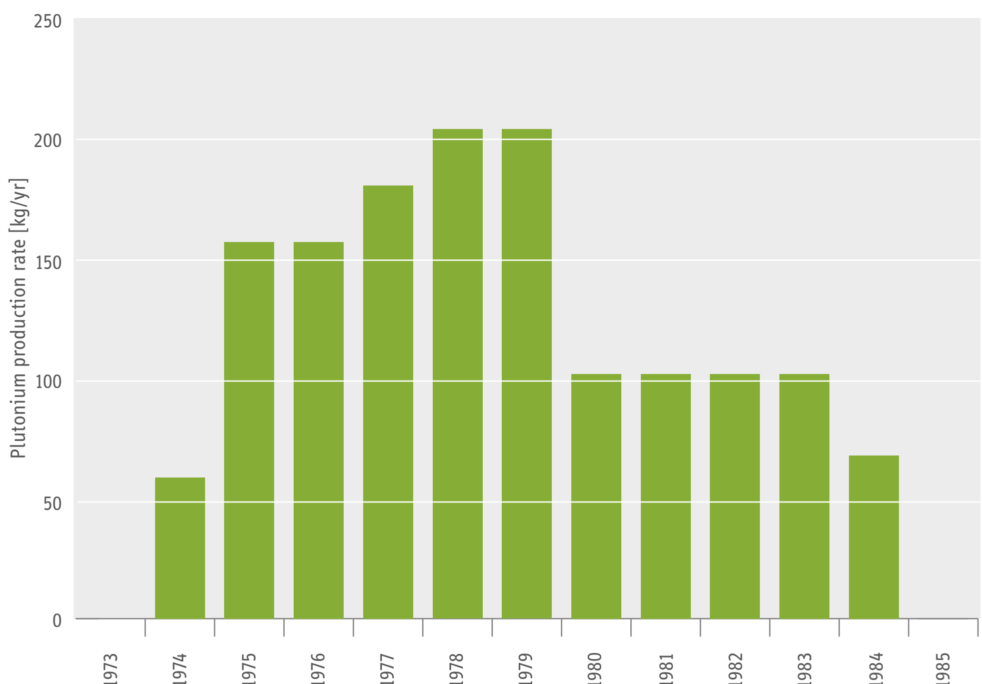

Figure 10. Reconstructed history of production of weapon-grade plutonium by Guangyuan reactor (kg/year). The reactor reached its design power of 600 MWt by October 1974. The plutonium-production rate was increased by 30 percent by 1978. Under the military-to-civilian conversion policy, the reactor reduced its plutonium production in the 1980s and was likely shut down in September 1984.

Summary of plutonium production

Together, the Jiuquan and Guangyuan reactors produced a total of about 3,800 GWt-days of fission. If China used the reactors only for plutonium production, it would have produced about 3.4 tons of weapon-grade plutonium. It has been reported, however, that China used the reactors to produce tritium for weapons as well.[152] Assuming 4 to 8 grams of tritium per warhead, this would reduce China's estimated production of weapon-grade plutonium by 120–240 kg.[153] This would reduce China's estimated plutonium production to about 3.2 tons.

The uncertainties of the above estimates mainly come from the assumptions concerning the phase-out of plutonium production during the 1980s. There is no available information on the specific reductions during the period. It has been assumed that the reactors reduced their plutonium production rate by 50 percent. If one assumes a range of 25 to 75 percent, the estimate could decrease or increase by 560 kg, resulting in a 17 percent uncertainty. Other uncertainties are with the reactor powers, capacity factors, burnups, and levels of tritium production during specific periods. This could increase the uncertainty to ±20 percent. In that case, China produced 3.2±0.6 (2.6 to 3.8) tons of weapon-grade plutonium. This is significantly higher than the author's estimates in 2010 and other recent estimates.[154]

Consumption and losses of plutonium

Some of the plutonium produced was lost in reprocessing and fabrication processes. Some was used in nuclear tests.

Reprocessing and fabrication losses. There is no information available about the recovery rates of plutonium in China's reprocessing facilities. According to the Russian experience, more than 10 percent of the plutonium was lost in the high-level waste during the 1950s, and the losses were reduced to 3–5 percent by the mid-1960s.[155] China's case might be similar. The Guangyuan plant focused on increasing its plutonium recovery rate until the 1980s.[156] The plutonium recovery rate at the civilian pilot reprocessing plant at the Jiuquan complex has not been good. The design of that plant was based primarily on the PUREX test facilities developed in the 1960s for the nuclear-weapon program. It has a design capacity to process up to 400 kg of spent fuel per day (the same as that of the small military facility).[157] During its 2010 hot test, reprocessing operations at the civilian pilot plant stopped after only 10 days due to problems with the large amount of waste produced and the high percentage of material unaccounted for.[158]

An additional quantity of plutonium was lost during the fabrication of plutonium for weapons. The US and Russia lost about 5 percent in fabrication.[159] As a conservatively low estimate, if China lost 5 percent of its weapon plutonium during reprocessing and fabrication, the quantity of plutonium lost could be about 160 kg.

Use in nuclear tests. China carried out about 38 nuclear tests after it began producing plutonium. Most of these tests would have contained weapon-grade plutonium in a simple fission weapon, in a compact boosted fission weapon, or as the fission primary in a two-stage thermonuclear weapon. A total of about 200 kg of plutonium would have been used in these tests, assuming an average of 5 kg of weapon-grade plutonium per test.[160]

Plutonium inventory. Assuming 160 kg of plutonium lost in reprocessing and fabrication and 200 kg in China's nuclear tests, China's current inventory of weapon-grade plutonium would be about 2.9±0.6 tons (2.3–3.5 tons). This estimate is at the high end of the U.S. Department of Energy's estimated range in 1999 of 1.7–2.8 tons of weapon plutonium.[161] It also is higher than other recent non-governmental estimates.[162]

Unfinished plutonium-production projects

During the third-line construction campaign (from the mid-1960s to the end of the 1970s), China tried to build several underground reactors but never finished them:

- Plant 816 in the Fuling district of Chongqing. This plant included a plutonium-production reactor and the associated reprocessing facilities in caves.
- Plant 827 near Yichang in Hubei province. China planned to build two heavy-water reactors in caves, one for tritium production and the other for civilian nuclear power. There also were plans to build a radiochemical research institute aboveground, focusing on research and development on reprocessing the spent fuel of power reactors.
- Project 820 at a nuclear research and experimentation center of Tsinghua University (coded as "base 200"), located at Changping, a suburb of Beijing. This project was supposed to construct a 50 MWe thorium molten-salt breeder reactor for electricity generation and to serve as a candidate for an advanced naval power reactor.

Plant 816. In 1966, to back up the Jiuquan plutonium-production plant, Beijing decided to build another plutonium-production complex (Plant 816), including a reactor and associated reprocessing facilities in caves under a mountain at Baitaozhen in Fuling, 130 km from Chongqing city.[163] The plant was to be located inside the Jinzi Mountain east of Wujiang River, a branch of the Yangtze River. The area is frequently shrouded by a thick fog, which facilitates concealment of activities from reconnaissance satellites. Construction started in February 1967. Like the Jiuquan reactor, Reactor 816 was to be a natural uranium-fueled, graphite-moderated, and water-cooled reactor with a power of 600 MWt with 100 MWe of electricity generating capacity.[164]

The construction of Plant 816 progressed very slowly due to the difficult work of mining out its caverns. This led to Beijing's decision in 1968 to shift priority to building the above-ground Guangyuan plant. Following its decision to shift from military to civilian production, Beijing decided to suspend the unfinished project in June 1982 and to end it in June 1984. By then about 85 percent of the civil engineering work had been finished and more than 60 percent of the plant equipment had been installed.

The reactor was never loaded with fuel. The 150-meter high stack is still on top of the mountain. The area of the man-made caves is 104,000 square meters. The main hall has nine levels with a combined height of about 70 meters. Reportedly, the cave was designed to withstand an air explosion of a 1-megaton hydrogen bomb or an 8-magnitude earthquake. More than 60,000 soldiers and scientists were involved in the plant's construction, and the total investment was about 740 million yuan, about $110 million (2017 $). In the late 1980s, the plant was converted to non-nuclear civilian purposes, including fertilizer production. Since 1993, the plant has been renamed as Chongqing

Jianfeng Chemical Co., Ltd. The project was declassified in 2002 and part of the site was opened as a domestic tourist attraction in 2010.

Figure 11.1. The area of Plant 816 near Baitaozheng, Fuling district of Chongqing. This image was taken on 24 March 2015 by a DigitalGlobe satellite (coordinates: 29° 33' 15.92" N /107° 30' 20.32" E). Credit: DigitalGlobe and Google Earth. The image shows the entrance to the underground nuclear facility. The stack, which is about 150 m high, is still on the top of the mountain.

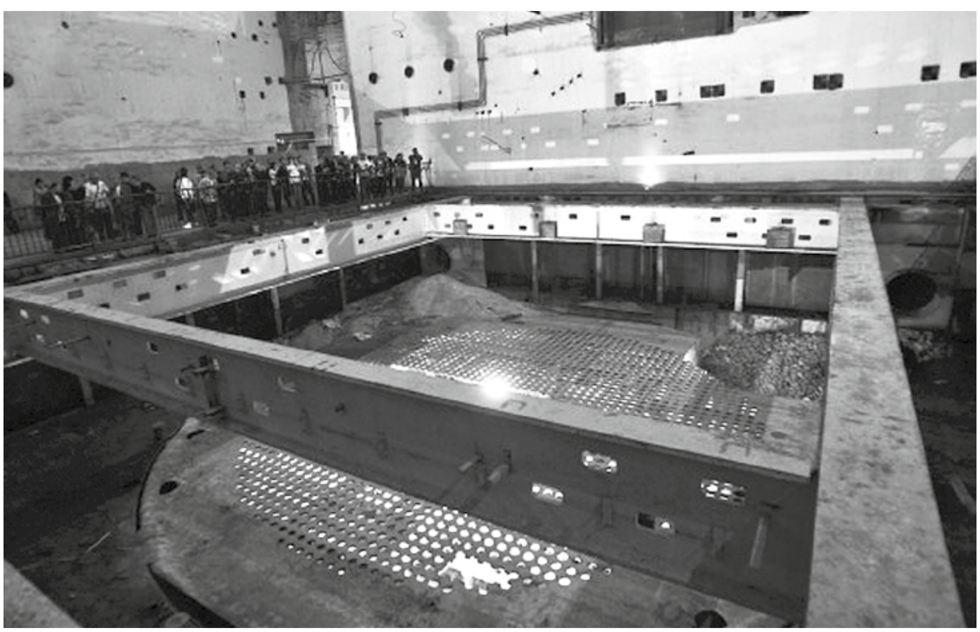

Figure 11.2. Top of Plant 816 reactor core. Source: sina.com.cn.[165]

Plant 827. In 1970, Beijing started Project 827: the construction of two heavy-water reactors – a military tritium-production reactor and a civilian power reactor – and a radiochemical research institute near Yichang in Hubei province, a third-line area near the Xiling Gorge, one of the famous three gorges of the Yangtze River. It was referred as "two reactors and one chemical engineering project" (Liang dui yi hua).[166] The project has been described as an early effort to explore and develop nuclear power in China.[167]

Some accounts state that the production reactor was for plutonium production.[168] Available information suggests, however, that it was a military heavy-water tritium-production reactor.[169] There is no available information about the design power of this production reactor. It is reported that during the 1970s, China studied the possibility of building a natural-uranium heavy-water reactor of 137 MWt[170] that could have served as a production reactor. If so, the reactor could have met the tritium needs of China's weapon arsenal during the period.[171]

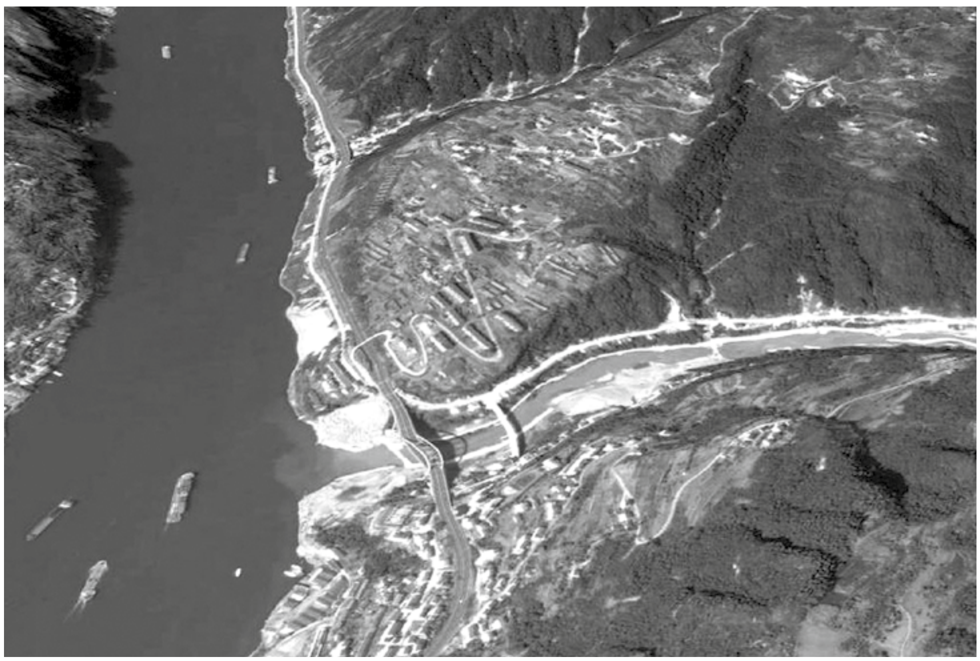

Figure 12. Plant 827 near Shaijingping area, Yichang, Hubei province. This image was taken on 11 November 2016 by a DigitalGlobe satellite (coordinates: 30° 50' 55.54" N /111° 08' 53.94" E). Credit: DigitalGlobe and Google Earth. The unfinished project to build reactors in caves is not visible in this image.

To secure the electrical supply for Plant 827, in June 1970, local governments worked intensively on their electricity-transmission system. In December 1970, construction on Plant 827 started.[172] China planned to build the two reactors in caves and locate the radiochemical research institute downstream beside the Yangtze River.[173] It should be noted that this research institute was likely intended to do R&D on reprocessing the spent fuel of power reactors.[174] In the early years, the project focused on road building, electricity and water supply, and a communications system. By around 1973, the project had built a dedicated railroad to Yichang, a paved road of about 97 km through the remote mountain area, and a huge freight depot near Yichang.[175]

To support the design of the heavy-water production reactor of Plant 827, a heavy-water zero power reactor (HWZPR) was built at CIAE and went critical in June 1970.[176] From 15 May 1973 to 15 June 1974, the HWZPR conducted 59 criticality tests for a total of about 410 hours simulating a heavy-water production reactor fueled with natural-uranium fuel. In the late 1970s, China changed its plans for Plant 827 and considered using 90 percent HEU in the production reactor. The CIAE redesigned its HWZPR by using HEU fuels from the HFETR. The new critical assembly went critical in September 1978 and completed its physics experiments by the end of 1981.[177] During this period, the HWZPR conducted 200 criticality tests for about 1224.6 hours, simulating Plant 827's production reactor using HEU fuel.[178] The shift to using 90 percent HEU in the heavy-water production reactor suggests that the Plant 827 reactor was intended mainly for tritium production.

In 1977, there was a proposal to build a 125 MWe heavy-water power reactor in Hunan province (the neighbor of Hubei province) as part of Project 827. This proposal to relocate the reactor came after a decision in 1974 to resume construction of the Gezhou Dam hydropower station on the Yangtze River in the Yichang area. The work on the dam had been suspended in November 1972. After the dam was built, there was no urgent need for a power reactor in the region. In addition, China's decision to choose light-water rather than heavy-water reactors for power might also have contributed to the slow progress of Project 827 and finally its end.[179]

Meanwhile, on 8 February 1970, Premier Zhou emphasized that China needed to develop nuclear power as well as weapons. Shanghai initiated Project 728 (based on the date of Zhou's proposal) to study various types of power reactors. In 1974, Beijing approved Project 728 to build a 300-MWe PWR based on China's experience from its naval-reactor program. Construction began on the 300 MWe PWR at Qinshan near Shanghai in 1984.

Following its military-to-civilian conversion decision, in the early 1980s, Beijing decided to suspend and end those third-line nuclear facilities still under construction. Project 827 was ended around 1982. Its two heavy-water reactors were still at the design stage. In the 1990s, China purchased two 728-MWe Candu heavy-water reactors from Canada.

Project 820. In November 1969, Beijing decided to construct a 50 MWe thorium molten-salt breeder at "Base 200" of Tsinghua University.[180] It planned to build the reactor in a cave. The plan was to spend about 100,000 yuan and start to supply electricity to Tiananmen Square by 1 July 1970.[181] The design was also a candidate for an advanced naval power reactor. After considerable effort, however, the project was abandoned by 1979. It cost about 200 million yuan, and military engineers dug a big cave – 20 meters wide, 30 meters high and more than 100 meters long – for the planned reactor.[182] In 1995, construction began on a prototype 10 MWe high-temperature gas-cooled reactor (HTR-10) aboveground at Base 200. The reactor achieved criticality in 2000.

Civilian plutonium production, stockpiles, and plans

China is actively pursuing a reprocessing policy for separating plutonium from the fuel of its light-water power reactors and its planned sodium-cooled breeder reactors.[183] China has had a policy of "closing" its fuel-cycle with plutonium separation and use as fuel since 1983. In December 2010, it began testing a pilot civilian reprocessing plant in the Jiuquan complex with a capacity to process 50 tons of spent fuel and separating out about 500 kilograms of plutonium per year. The plant has been shut down by technical problems most of the time since then, however. As of the end of 2015, it had separated 25.4 kilograms of plutonium.[184] China has built a pilot uranium-plutonium mixed-oxide (MOX) fuel fabrication facility nearby, with a design capacity of 0.5 tons of MOX per year. This pilot MOX plant is intended to supply fuel for China's Experimental Fast Reactor (CEFR). China's Institute for Atomic Energy (CIAE), which operates the CEFR, has had several research projects on the different stages of MOX fuel fabrication and planned to load test rods of MOX into the CEFR for irradiation before 2017.[185] As of late 2017, MOX test fuel had not yet been loaded in to the CEFR.

In early 2015, the government approved the construction of a demonstration reprocessing plant at Jinta in Gansu Province with a capacity of 200 tons heavy metal (tHM) per year. CNNC started site preparation for the project in July 2015.[186] It is supposed to be operational in 2020.

Since 2007, CNNC has been negotiating with France's AREVA over the purchase of a commercial reprocessing plant with a capacity of 800 tons of spent fuel per year. CNNC and AREVA have yet to reach an agreement, however, on the price. CNNC plans to start construction in 2020 and, since the summer of 2015, has been considering potential sites along China's east coast. One of these sites, in Lianyungang in Jiangsu province, was withdrawn from consideration in August 2016 after a protest by thousands of citizens.[187]

If China did succeed in building and operating its 200 tHM/year and 800 tHM/year reprocessing plants at their design capacities, they would separate about 2 and 8 tons of plutonium per year, respectively, and quickly create a civilian inventory of separated plutonium much larger than China's military stockpile.

CNNC also has active plans for sodium-cooled breeder reactors. Since 2010, the CIAE has operated the China Experimental Fast-neutron Reactor (CEFR). It is a small sodium-cooled, experimental reactor located about 40 km from Beijing with a power capacity of 25 MWe (65 MWt). The CEFR went critical in July 2010, 10 years after the start of its construction, and by July 2011 was operating at 40 percent of its full power and was connected to the grid. The reactor was online for only 26 hours during 2011, however, producing the equivalent of one full-power hour. It was disconnected from the grid during 2012 and 2013.[188] During the four-day period 15–18 December, 2014, the CEFR successfully completed a test at full power for 72 hours.[189] It continues to operate intermittently at somewhat lower power levels for R&D purposes.[190]

CNNC had planned to start construction in 2017 on a 600 MWe demonstration fast reactor, the CFR-600, at Xiapu in Fujian province with commissioning planned for 2023.[191] However, as of late 2017, no official permission had been issued for reactor construction. CNNC also plans to develop a 1000 MWe CFR-1000.[192] Since 2008, CNNC has negotiated with Rosatom, Russia's state nuclear power corporation, over the purchase of a copy of Russia's BN-800. Chinese experts argue that Russia's price is too high, however.

Summary

China has not officially declared that it has ended HEU and plutonium production for weapons. It appears, however, that China stopped its military plutonium production in 1987 and subsequently decommissioned its military plutonium-production complexes. The Lanzhou enrichment plant ended HEU production around 1980 and continued to produce LEU until it was closed in 2000. The Heping enrichment plant appears to have stopped HEU production for weapons in 1987 and since then has been producing LEU and HEU for military non-weapon use and possibly civilian use.

Newly available public information on the history of China's HEU and plutonium production permits updates of the 2010 IPFM estimates that China has stockpiles of 16±4 tons of weapon-grade HEU and 1.8±0.5 tons of weapon-grade plutonium. The new estimates are that China currently has about 14±3 tons of weapon-grade HEU and 2.9±0.6 tons of weapon-grade plutonium.

These new estimates do not change the earlier conclusion that China may have smaller military stockpiles of HEU and plutonium than Britain, France, Russia, and the United States.

About the author

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Endnotes

1. China's official nuclear history is Li Jue, Lei Rongtian, Li Yi, and Li Yingxiang, eds., *China Today: Nuclear Industry*, China Social Science Press, Beijing, 1987 (in Chinese). Selections were translated and published by the U.S. Foreign Broadcast Information Service, JPRS-CST-88-002, 15 January 1988; and JPRS-CST-88-008, Washington, DC, 26 April 1988.

2. Li et al., eds., *China Today: Nuclear Industry, op. cit*., pp. 70–74.

3. Zheng Jingdong, the blog "The Days of Racing to Complete the Plant 821," 26 November 2009. www.wyzxwk.com/Article/lishi/2009/11/110302.html (in Chinese).

4. See, for example, the blog "Tracing the Origin of Jinkouhe District of Leshan City," http://xzqh.info/bbs/read.php?tid=134140 (in Chinese).

5. Wang Zhaofu, "60 Years of New China's Nuclear Energy Development Key Events," *China Nuclear Energy,* No. 5, 2009, http://www.china-nea.cn/html/2009-11/4239.html (in Chinese).

6. More can be found at interviews and discussions by the Chinese television station CCTV-10 with experts and former solders involved in Project 816. See http://tv.cntv.cn/video/C24886/d393d975879c40a01e674083c59c91f5 (in Chinese); and Peng Yining, "Nuclear Reaction to Tourist Attraction," *China Daily*, 22 June 2010, http://www.chinadaily.com.cn/china/2010-06/22/content_10000276.htm.

7. Zheng, "The Days of Racing to Complete the Plant 821," *op. cit.*

8. Hui Zhang, "China's Uranium Enrichment Complex," *Science & Global Security*, vol. 23, 2015, pp. 171–190.

9. Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 79.

10. *Ibid*., pp. 80–86.

11. Jing Yongyu, et al., "Economic Analysis on Decommissioning of Lanzhou Gaseous Diffusion System," *Proceedings of Workshop on Recycling Economics,* Chinese Nuclear Association, Beijing, 1 July 2008 (in Chinese).

12. Wang, "60 Years of New China's Nuclear Energy Development Key Events," *op. cit.*

13. See, for example, Cheng Lili, "Plant 814: The New Era of 'Small Yan'an'" *Workers' Daily,* 26 March 2010 (in Chinese). This source makes it clear that the plant had continued operating since 1987. However, it does not describe clearly the specific purposes.

14. Zhang, "China's Uranium Enrichment Complex," *op. cit.*

15. For more details, see Zhang, "China's Uranium Enrichment Complex," *op. cit.* As of the end of 2016, Lanzhou CEP capacity was about 2.6 million SWU/year, Hanzhong plant 405 was about 2 million SWU/year and the Emeishan plant had a capacity of 0.8 million SWU/year.

16. Yingxiang Li, "The Frustrated Course to Start Uranium Enrichment Plant," *China Nuclear Industry,* no. 7, 2008, pp. 56–59 (in Chinese).

17. *Ibid.*

18. *Ibid.*

19. *Ibid.*

20. Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 168.

21. *Ibid.*, p. 169.

22. *Ibid.*, p. 172.

23. *Ibid.*, p. 176.

24. Magical Sword Literary and Art Society of Nuclear Industry, ed., *The Secret Course* (2nd ed.) (Beijing: Atomic Energy Press, 1993), pp. 102–115 (in Chinese).

25. Wang, "60 Years of New China's Nuclear Energy Development Key Events," *op. cit.*

26. See, for example, Zhou Zhi, "Recollections of the Pioneering Work of Plant 404," Journal of Yan Huang Chunqiu, No. 2, 2007. The author was former vice minister of the Ministry of Nuclear Industry, http://qkzz.net/Announce/Announce.asp?BoardID=17100&ID=10015168 (in Chinese).

27. Li et al., eds., *China Today: Nuclear Industry, op. cit.*, p.168.

28. *Ibid.*, p. 176.

29. CNNC, "Deng Xiaoping and China's Nuclear Industry," *Xinhua Net*, 19 August 2003, http://news.xinhuanet.com/newscenter/2003-08/19/content_1034042.htm (in Chinese).

30. Zhaohui Cui (a former senior engineer at Plant 404), "The Life of Sanbei," http://qxzc.net/gr/cuizh/4/4%286%29.htm (in Chinese).

31. While the United States monitored the progress of the diffusion plant beginning around 1959, it assumed the cascade building was not large enough to host cascades to produce weapon-grade materials. This led to some surprise when U.S. air sampling of debris from China's first nuclear explosion identified it as a uranium-based bomb. See, for example, William Burr and Jeffrey Richelson, "Whether to 'Strangle the Baby in the Cradle'," *International Security,* vol. 25, no. 3, Winter 2000/01, p. 91. In December 1964, a U-2 equipped with infrared detection systems confirmed that the Lanzhou GDP was indeed operating. See, for example, R.E. Lawrence and Harry W. Woo, "Infrared Imagery in Overhead Reconnaissance," *Studies in Intelligence,* vol. 11, No. 2, Summer 1967, pp. 17–40.

32. Charles Murphy, "Mainland China's Evolving Nuclear Deterrence," *Bulletin of the Atomic Scientists,* January 1972, pp. 28–35.

33. U.S. Defense Intelligence Agency, "People's Republic of China Nuclear Weapons Employment Policy and Strategy," Report no. TCS-654775-72, Washington, DC, March 1972.

34. Li et al., eds., *China Today: Nuclear Industry, op. cit.*, p. 179.

35. In 2001, a Russian-supplied centrifuge facility (0.5 million SWU/year) was commissioned at the Lanzhou enrichment plant, which was said to have twice the capacity of the GDP. Since 1984, the GDP had increased to 2.5 times the original design capacity (as described in this report). Thus, it can be estimated that the Lanzhou GDP had an original design capacity of about 100,000 SWU/year. See Zhang, "China's Uranium Enrichment Complex," *op. cit.*, and "Establishment of Uranium Enrichment Base Gradually Entering Better Stages and Going Abroad," *China Electric Power News Network,* 25 August 2015, www.heneng.net.cn/index.php?mod=news&category_id=9&action=show&article_id=36529 (in Chinese).

36. Li et al., eds., *China Today: Nuclear Industry, op. cit*., p. 179.

37. *Ibid.*

38. CNNC, "Deng Xiaoping and China's Nuclear Industry," *op. cit.*

39. Li et al., eds., *China Today: Nuclear Industry, op. cit*., p. 180.

40. Li et al., eds., *China Today: Nuclear Industry, op. cit*., pp. 179–184.

41. CNNC Lanzhou Uranium Enrichment Co., Ltd., "The Cradle of China's Uranium Enrichment," *The Literature and History of Xigu,* March 4, 2013, http://zx.xglzgs.gov.cn/wszl/2013-03-04/47522.htm (in Chinese). Another reporter mentioned that the plant realized the goal of "one plant [becoming] two" by 1978. For details, see Xie Wuzhan, "Plant 504: The Leading Runner of the Cause of China's Uranium Enrichment," *Gansu Daily,* 31 May 2008 (in Chinese). However, as described in this report, the plant could have increased its output by around 70 percent by 1980 by raising cascade flow rates and improving separation membranes. This is consistent with the statement regarding the Heping GDP that "one plant became 1.5 plants" by 1980. The reporter could have been rounding the number from 1.5 or 1.7 to 2.

42. Jing Yongyu et al., "Radiation Protection and Monitoring during Decommissioning of the Diffusion System at Lanzhou Enrichment Plant," *Proceedings of National Workshop on the Decommissioning Plans of Nuclear and Radiation Facilities,* Chinese Nuclear Association, Mianyang, Sichuan, 1 November 2007 (in Chinese).

43. Jing, "Economic Analysis on Decommissioning of Lanzhou Gaseous Diffusion System," *op. cit.*

44. Ibid. While CNNC stopped operations at this GDP and removed the nuclear materials, it has not removed those gaseous-diffusion units. Thus, according to the definitions of the *IAEA Safeguards Glossary,* the Lanzhou GDP should be categorized as a "closed-down" facility rather than a "decommissioned" one. According to the glossary, a "closed-down facility (or closed-down location outside facilities)" is "an installation or location where operations have been stopped and the nuclear material removed but which has not been decommissioned." A "decommissioned facility (or decommissioned location outside facilities)" is "an installation or location at which residual structures and equipment essential for its use have been removed or rendered inoperable so that it is not used to store and can no longer be used to handle, process or utilize nuclear material." See International Atomic Energy Agency (IAEA), *IAEA Safeguards Glossary 2001 Edition,* International Nuclear Verification Series No. 3, www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/Start.pdf), p. 36. In this report, define a shut-down facility is one where operations are temporarily stopped and able to resume operation, while a closed-down or decommissioned facility is defined as in the *IAEA Safeguards Glossary 2001 Edition*.

45. The specific assumptions for the figure are the following:
From 1964 through 1965, about 25,000 SWU/yr at a tails assay of 0.4 per cent;
From 1966 through 1970, a linear increase to 50,000 SWU/yr at a tails assay of 0.3 per cent;
From 1971 through 1975, a linear increase to the design output of 100 ,000 SWU/yr at a tails assay of 0.3 per cent;
From 1976 through 1979, a linear increase from 100,000 to 170,000 SWU/yr at a tails assay of 0.3 per cent;
From 1980 through 1984, a linear increase from 170,000 to 200,000 SWU/yr;
From 1985 through 2000, a linear increase from 203,000 to 250,000 SWU/yr.

46. Zhang, "China's Uranium Enrichment Complex," *op. cit.*

47. National Nuclear Safety Administration (NNSA), *Annual Report 2008,* http://haq.mep.gov.cn/haqkw/200911/t20091113_181615.htm (in Chinese).

48. Hui Zhang, "Assessing China's Uranium Enrichment Capacity," Institute for Nuclear Materials Management 57th Annual Meeting, Atlanta, Georgia, USA, 24–28 July, 2016.

49. CNNC, "Deng Xiaoping and China's Nuclear Industry," *op. cit.*

50. "Tracing to the Origin of Jinkouhe District of Leshan City," *op. cit.*

51. Wang, "60 Years of New China's Nuclear Energy Development Key Events," *op. cit.*

52. As shown below, after a capacity increase of a factor of 1.5, the enrichment capacity was 0.16 million SWU/year.

53. U.S. Defense Intelligence Agency, *People's Republic of China Nuclear Weapons Employment Policy and Strategy, op.cit.*

54. In a discussion of the contribution to enrichment plants by Kang Zujie, a former leader of Plant 405 who also was involved in the construction and operation of Plants 504 and 814, it said that Kang played a key role in achieving the plant's goal of "one plant becomes one and half plants" during the Fifth Five-Year Plan (1976–1980). See http://blog.sina.cn/dpool/blog/s/blog_6ce13f9b01016yaw.html (in Chinese).

55. Considering the combination of an increase of 45 percent in the Heping GDP's production capacity with the capacity of the pilot CEP and the first larger commercial CEP near the city of Emeishan (see below), it has been reported that Plant 814 increased its total production capacity to eight times the production capacity of the Heping GDP before 2001. See Sichuan National Defense Workers' Union, "The Backbone of National Defense: The Story of Du Weihua, a National Labor Model and Director of CNNC Plant 814," *News of China Defense Industry,* Postal and Telecommunications Workers' Union, 25 May 2010. http://gfyd.acftu.org/ (in Chinese).

56. The available information shows that, to deepen the military-to-civilian conversion policy, the central government made official decisions on ending plutonium production in 1987 (as discussed in following sections). The Lanzhou GDP started LEU production for civilian use around 1980. Thus, an end to HEU production for weapons at the Heping GDP in 1987 is reasonable and consistent with Beijing's policy on further reduction and eventual ending of fissile-material production after 1985 (see, Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 83). It also is consistent with numerous discussions between the author and Chinese experts conducted in recent years.

57. Sichuan National Defense Workers' Union, "The Backbone of National Defense: The Story of Du Weihua, a National Labor Model and Director of CNNC Plant 814," *op. cit.*

58. *Ibid.*

59. Zhang, "Assessing China's Uranium Enrichment Capacity," *op. cit.*

60. *Ibid.*

61. From June 1970 through 1975, a linear increase from 50,000 to its original design capacity of 110,000 SWU per year at a tails assay of 0.3 per cent;
From 1975 through 1980, a linear increase from 110,000 to 160,000 SWU/yr at a tails assay of 0.3 per cent;
From 1981 to 1987 the plant operated at 160,000 SWU/yr at a tails assay of 0.3 per cent;
After HEU production stopped, the plant continued to operate at this level until 2000;
From 2001 through 2003, a linear increase from 160,000 SWU/yr to 230,000 SWU/yr;
From 2004 to 2016 the plant operated at 230,000 SWU/yr.

62. Li et al., eds., *China Today: Nuclear Industry, op. cit*., p. 186.

63. Assuming Chinese plutonium-production reactors similar to those at Tomsk-7 in Russia, the discharged uranium had a burnup of 468 MWd/ton and contained 420 grams of plutonium per ton of uranium. See Anatoli Diakov, "The History of Plutonium Production in Russia," *Science & Global Security,* vol.19, January–April 2011, pp. 28–45. Thus, producing about 3.2 tons plutonium (as discussed in following section) would have resulted in about 7,600 tons of reprocessed uranium. Moreover, assuming the depleted uranium was 0.65 percent U-235, to enrich all of this uranium to 90 percent HEU, with a tails assay of 0.3 percent, would require about 0.3 million SWU more than would be required to produce the same amount of HEU from natural uranium. It is not clear how much spent uranium has been recovered. It is assumed about half of the spent uranium had been recovered.

64. See, for example, Xiao Xunze, "China's First Zero-Power Fast Critical Reactor," in Fast Reactor Division, China Atomic Energy Authority, ed., *The 45 Years of CIAE Fast Reactor Progress* (Beijing: Atomic Energy Press, 2011), p. 30.

65. NNSA, Annual Report 2015. http://nnsa.mep.gov.cn/zhxx_8953/haqnb/201608/P020160830340792893561.pdf.

66. For example, the HFETR reached criticality in 1979 and converted to LEU fuel in 2007. The HFETR would have used about 994 kg of 90 percent HEU before conversion. See Zhang, "China's HEU and Plutonium Production and Stocks," op. cit. However, it could use about 284 kilograms of 90 percent HEU before 1987. The MJTR achieved criticality in 1991 and converted to LEU fuel in 2007. However, it operated after 1987 and was fueled with the HFETR spent fuels. Also, the Pilot Reprocessing Plant Nuclear Criticality Safety Experiment Facility operated after 1987. In addition, China had operated one Zero-Power Fast Critical Reactor, which has a core of

50 kg of 90 percent U-235. Moreover, since 1984, China has had four Miniature Neutron Source Reactors (MNSRs). Each requires a long-lived core containing about 1 kg of 90 percent HEU. Two of them have shut down, one was converted in March 2016, and the remaining one is being converted with U.S. cooperation. In addition, China had sold one MNSR each to Ghana (1995), Iran (1994), Nigeria (1996), Pakistan (1989), and Syria (1996). But all of these took place after 1987 (except of the one at the CIAE in 1984). In July 2016, the MNSR in Ghana was converted, and China has said it will help others who want to convert. In short, a total of about 335 kg of 90 percent HEU could be available for those research reactors before 1987, which would correspond to about 64,000 SWU at a tails assay of 0.3 percent.

67. NNSA et al., "Comprehensive Safety Inspection Report on Civilian Nuclear Facilities," 2012, www.mep.gov.cn/zjyj/201206/W020120615619308262677.pdf (in Chinese); *Annual Report 2015, op. cit.;* IAEA Research Reactor Data at http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx.

68. Magical Sword Literary and Art Society of Nuclear Industry, *The Secret Course, op. cit.*, p. 301.

69. Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 239.

70. Li et al., eds., *China Today, Nuclear Industry, op. cit.,* pp. 305–306.

71. Sun Qin, ed., *The Nuclear Casting a Dream of Powerful Nation* (Beijing: Atomic Energy Press, 2015) (in Chinese). In this book, Zhang Jinlin, an academician of the Chinese Academy of Engineering and the chief designer of the second-generation nuclear-powered submarine, emphasized that the most exciting events he was involved in included the first second-generation nuclear submarine (SSN) delivered to the Navy in 2006. President Hu Jintao came to the flag ceremony. The first SSBN of second generation (the Type 094 Jin-class) was delivered in 2014 and Zhang with his team were received by President Xi Jinping.

72. "Military and Security Developments Involving the People's Republic of China 2015," Annual Report to Congress, U.S. Department of Defense, 2016, https://www.defense.gov/Portals/1/Documents/pubs/2016%20China%20Military%20Power%20Report.pdf, p. 26.

73. This assumes that the Lanzhou GDP stopped HEU production around 1980. Later it could have produced LEU for naval reactors. Also see details in Zhang, "China's HEU and Plutonium Production and Stocks," *op. cit.,* endnote 39.

74. See, for example, "China's First Generation of Nuclear Submarine Development Process: Mao Zedong Paid Special Attention," military.china.com, 4 March 2015, http://military.china.com/history4/62/20150304/19345213_all.html (in Chinese).

75. It is assumed the reactor operates with an average output of one-sixth of full power, the spent fuel has a U-235 burnup of 50 percent, and 1 kg of U-235 fission generates about 940 megawatt-days of energy. See, for example, Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review,* Spring 2001, p. 95.

76. For natural-uranium feed, producing 1 kg of 5 percent LEU requires 7.2 SWU with a tails assay of 0.3 percent.

77. Yu Yan, "Some Feelings on Visit and Practice in Chengdu's NPIC," 1 September 2010, http://hjxy.usc.edu.cn/info/1035/1547.htm (in Chinese).

78. Jiang Weimin, ed., *Commemorating the First Anniversary of Liu Huaqing's Death* Beijing: PLA, 2011 (in Chinese).

79. "Our Small Reactor Projects May Be Blossoming; the Purpose is the Key for Site Selection," *China Energy Newspaper,* 30 November 2011, www.nea.gov.cn/2011-11/30/c_131278758.htm (in Chinese).

80. "CNNC Small Multi-purpose Modular Reactor ACP100 Passes IAEA Safety Review," cnnc.com.cn, 28 April 2016, http://en.cnnc.com.cn/2016-04/28/c_51725.htm.

81. CNNC, "ACP100 Technical & Economic Aspects," paper delivered at the Technical Meeting on Economic Analysis for HTGR and SMR, Vienna, 25–28 August, 2015, https://www.iaea.org/NuclearPower/Downloadable/Meetings/2015/2015-08-25-08-28-NPTDS/DAY2/2._ACP100_technical_and_economic_aspects.pdf.

82. Zhu Xuerui, "The Curtain Has Risen to Apply Small Reactor," *China Energy Newspaper,* 1 August 2011, http://paper.people.com.cn/zgnyb/html/2011-08/01/content_885404.htm (in Chinese).

83. Zhang, "China's HEU and Plutonium Production and Stocks," *op. cit.*

84. Song Yunzhi, a senior engineer, once received national awards due to his major contribution to the use of Reactor 801 for mass production of tritium and saved investment of 0.5–0.8 billion yuan for the military tritium production reactor of Project 827. See Song, *Dictionary of World Excellent Experts,* no. 526, January 2007, www.8999.net/bbs/ShowPost.asp?PageIndex=36&threadid=1262&SortOrder=1(in Chinese). Other accounts address China's use of its graphite-moderated production reactor to produce plutonium and tritium. See,
for example, a blog post on China's Plutonium and Tritium Production, 5 March 2012, www.network54.com/Forum/388055/thread/1330961586/%D6%D0%B9%FA%B5%B1%C4%EA%EE%D0%BA%CD%EB%B0%B5%C4%C9%FA%B2%FA+zt (in Chinese).

85. Assuming that one 1 GWe Candu reactor could produce annually about 180 grams of tritium. See Frank von Hippel, *Banning the Production of Highly Enriched Uranium,* IPFM Research Report No. 15, March 2016, note 51, http://fissilematerials.org/library/rr15.pdf.

86. For a nuclear arsenal of 250 warheads, the tritium stockpile would be about 1–2 kg – that is, 4–8 g for each of the 250 warheads. Tritium decays at a rate of 5.5 percent per year; therefore, such an arsenal needs a tritium production capacity of about 55–110 g/year to replenish the decay loss.

87. Jonathan Medalia, "Chinese Nuclear Testing and Warhead Development," CRS Report for Congress 97-1022 F, 14 November 1997,
http://www.nuclearfiles.org/menu//key-issues/nuclear-weapons/issues/testing/PDFs/CIA/Document26.pdf.

88. See details in Zhang, "China's HEU and Plutonium Production and Stocks," *op. cit.*

89. In the US enrichment program, "normal operating losses" were about 5 tons out of total production of about 1000 tons (from gaseous-diffusion plants), i.e. 0.5 % losses.

90. Simon Henderson, "Nuclear Scandal: Dr. Abdul Qadeer Khan," *The Sunday Times,* 20 September 2009.

91. For natural-uranium feed producing 90 percent HEU, at a given separative work capacity, a tails assay of 0.4 percent would produce about 13 percent more HEU than for a tails assay of 0.3 percent. Another major uncertainty is related to the production outputs during specific periods, which could eventually lead to an uncertainty of about 5 percent in the cumulative SWU production. Finally, it should be noted that a huge uncertainty in HEU stocks could come from the Heping GDP. It is assumed the plant stopped HEU production for weapons by 1987. Later, if it still produced mainly HEU, it would accumulate larger HEU stocks. For example, an enrichment capacity of 0.23 million SWU/year would produce about 1.2 tons of 90 percent HEU each year. Also, the pilot CEP with a capacity of 0.25 million SWU/year could produce about 1.3 tons of 90 percent HEU each year. Eventually, it would be significantly larger than assumed here and would be beyond the range given here.

92. This is significantly less than that the roughly 19.4±5 tons previously estimated by ISIS in Albright and Kelleher-Vergantini, *Military Highly Enriched Uranium and Plutonium Stocks in Acknowledged Nuclear Weapon States, op. cit.* One major reason for the higher estimate is that the assumed enrichment capacity of the Heping GDP is much larger than new available information suggests.

93. Zhang, "China's HEU and Plutonium Production and Stocks," *op. cit.*

94. Huang Jianchi and Xi Lisheng, "The Status of China's Production Reactor," *Advances in Earth Science,* 1990, no. 2, pp. 60–61, www.adearth.ac.cn/CN/article/downloadArticleFile.do?attachType=PDF&id=10091 (in Chinese). Both authors were on the expert panel on strategy for the State Council's nuclear power office. Huang was the panel director. Also, former senior engineer of Reactor 801, Cui Zhaohui described the design power of that reactor as 600 MWe. See Cui, "The Life of Sanbei", *op. cit.*

95. Matthew Bunn, Hui Zhang, and Li Kang, "The Cost of Reprocessing in China," Managing the Atom Project, Belfer Center for Science and International Affairs, January 2016. http://belfercenter.ksg.harvard.edu/files/The%20Cost%20of%20Reprocessing-Digital-PDF.pdf.

96. See IAEA, "Communication Received from China Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.7/15, IAEA, Vienna, 19 September 2015, https://www.iaea.org/sites/default/files/infcirc549a7-14.pdf.

97. More details about the history of the Jiuquan reactor can be found in Li et al., eds., *China Today: Nuclear Industry, op. cit.*, Chapter 10, pp. 204–215. See also Cui, "The Life of Sanbei," *op. cit.,* "Recollections of the Pioneering Work of Plant 404," *op. cit.*

98. Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 205.

99. *Ibid.* pp. 210–211.

100. See Cui, "The Life of Sanbei," *op. cit.*; Li et al., eds., *China Today: Nuclear Industry, op. cit.*, p. 210.

101. "Recollections of the Pioneering Work of Plant 404," *op. cit.*

102. See Cui, "The Life of Sanbei," *op. cit.*

103. Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 211.

104. See Cui, "The Life of Sanbei," *op. cit.*

105. Li et al., eds., *China Today: Nuclear Industry, op. cit.*, p. 212.

106. *Ibid,* p. 210.

107. *Ibid,* p. 214.

108. See for example, "Recollections of the Pioneering Work of Plant 404," *op. cit.*; Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 214.

109. Li et al., eds., *China Today: Nuclear Industry, op. cit.,* pp. 80–86.

110. "The 50th Anniversary Celebration of Plant 404," 25 October 2008, http://blog.sina.com.cn/s/blog_59d3d87c0100ax4j.html (in Chinese).

111. Li et al., eds., *China Today: Nuclear Industry, op. cit.*, p. 91.

112. *Ibid.*

113. *Ibid,* p. 86.

114. No electricity substation or transmission lines connected to the site have been seen on satellite images.

115. When one former worker visited the reactor on 8 November 1986, he said the reactor had then closed and ended its historic mission. See http://blog.sina.com.cn/wjx5511(in Chinese).

116. See "The 50th Anniversary Celebration of Plant 404," *op. cit.*

117. Song Xuebin, "Taking Root in the Gobi Desert for 50 Years Due Solely to the National Needs," *China Nuclear Industry,* no. 9, 2008 (in Chinese). Song is a former director of Plant 404.

118. Bai Zhiqiang, "Statistical Analysis of the Occupational Radiation Exposure of the First Stage of Reactor 801 Decommissioning," *Proceedings of National Workshop on Decommissioning Plans Nuclear and Radiation Facilities,* Chinese Nuclear Association, Mianyang, Sichuan, 1 November 2007 (in Chinese).

119. Li et al., eds., *China Today, Nuclear Industry, op. cit.,* p. 227.

120. Assuming Chinese plutonium-production reactors are the same as the reactors at Tomsk-7 in Russia, the discharged uranium would have a burnup of 468 MWd/ton and contain 420 g of plutonium per ton of uranium. See Diakov, "The History of Plutonium Production in Russia," *op. cit.*

121. Nuclear Threat Initiative, "China's Nuclear Tests: Dates, Yields, Types, Methods, and Comments," *op. cit.*

122. Li et al., eds., *China Today: Nuclear Industry, op. cit.*, p. 232.

123. See, "The 50th Anniversary Celebration of Plant 404," *op. cit.*

124. Hui Zhang and Frank von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Gaseous-Diffusion Plants," *Science & Global Security,* vol. 8, 2000, pp. 219–271. Figure A-2 shows that for a seasonal average temperature of 10 °C and a typical temperature increase between 5 °C and 15 °C, the amount of heat discharged by the cooling towers would range from 0.02 MWt/m^2 to 0.2 MWt/m^2. For a top diameter of 30 meters, this corresponds to 14–140 MWt for each tower.

125. Diakov, "The History of Plutonium Production in Russia," *op. cit.*

126. CCTV-10 interviews and discussions with experts and former solders involved in the Project 816, http://tv.cntv.cn/video/C24886/d393d975879c40a01e674083c59c91f5 (in Chinese).

127. Diakov, "The History of Plutonium Production in Russia," *op. cit.*

128. Communication by the author with CNNC experts, November 2016, Suzhou, China.

129. The estimate of power by the end of 1973 is based on the assumption that the reactor power increased linearly from 0.5 percent of design power in 1967 to full design power by June 1975. Considering the reactor shut down for 103 days during January 1974–April 1974 for repair and maintenance, the effective period is about 8.2 years over the period 1967 to June 1975.

130. As discussed above under the military-to-civilian conversion policy, since 1981 the central government has required a relatively large reduction of military nuclear-material production. See, for example, Li et al., eds., *China Today: Nuclear Industry, op. cit.,* pp. 80–86. It is reported that after entering 1980, Plant 404 decreased rapidly its plutonium production. See "The 50th Anniversary Celebration of Plant 404," *op. cit.* In practice, HEU production has decreased by about half since 1980. The Lanzhou and Heping GDPs had a similar production capacity, and the Lanzhou GDP was shifted from HEU to LEU production around 1980. Thus, based on the government policy and the HEU production cases, Reactor 801 could have reduced production significantly during the 1980s before it shut down. While detailed information on the reduction is not available, the reactor could have reduced production at a modest rate in the early 1980s and at a significant rate since the mid-1980s. It is assumed therefore that the reactor had an average reduction of plutonium production of around 50 percent during 1980–1986. If one assumes a range of 25 to 75 percent, the estimate could result in an uncertainty of about 10 percent to the total plutonium produced in China. In addition, if the reactor has been shut down for dual-use conversion work since 1984, there could have been further reductions.

131. It also assumes the amount of plutonium produced per MWt-day by the Jiuquan reactor is the same as for the EI-2 reactor at Tomsk-7 in Russia. At that reactor, it is estimated the discharged uranium had a burnup of 468 MWd/ton and contained 420 g of plutonium per ton of uranium. See Diakov, "The History of Plutonium Production in Russia," *op. cit.* Thus, the Jiuquan reactor is assumed to have produced 0.9 grams of plutonium per MWt-day.

132. See "Declassified Plant 821," *op. cit.*

133. More details of the history of Plant 821 can be found in the blogs of Zheng Jingdong, a senior engineer at Plant 821. Zheng's description of operations at Plant 821 would be reliable, given that Zheng had read through the first volume of the history of Plant 821 *"Plant 821 (1969–1987)"*. He also helped to edit the second volume of the history of Plant 821, *"Plant 821 (1988–2006)."* See Zheng's blogs: http://www.wyzxwk.com/author/c5/463.html (in Chinese), in particular, "Something Can Be Spoken – The Original Secrets of Nuclear Industry," June 4, 2011, http://www.wyzxwk.com/Article/lishi/2011/06/230375.html, and the second version at

http://bbs.tianya.cn/post-culture-410353-1.shtml; "The Days of Racing to Complete Plant 821," November 26, 2009 (http://www.wyzxwk.com/Article/lishi/2009/11/110302.html); and "Declassified Plant 821," 4 June 2011. (http://www.aiweibang.com/m/detail/1454501.html?from=p).

134. See, for example, "Something Can Be Spoken – The Original Secrets of Nuclear Industry," *op. cit.*

135. See, for example, Cui, "The Life of Sanbei," *op. cit.*

136. "The Days of Racing to Complete Plant 821,"*op. cit.*

137. See, "Something Can Be Spoken – The Original Secrets of Nuclear Industry," *op. cit.*

138. Huang and Xi, "The Status of China's Production Reactor," *op. cit.*

139. See, for example, "The Intelligent Life of Two Heroes of Nuclear Power," "Document Web of Jiangsu Public Science and Technology: People," 14 May 2007, http://hi.baidu.com/lovechild/blog/item/f43d1a7a00a1eaec2e73b359.html (in Chinese). See also Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 210.

140. See, for example, "The Intelligent Life of Two Heroes of Nuclear Power," op. cit.; see also "The Days of Racing to Complete Plant 821," *op. cit.*

141. "The Days of Racing to Complete Plant 821," *op. cit.*

142. Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 91. It addressed the conversion work of the plutonium-production reactor that started in September 1984 and was supposed to be completed in 1987. But the book did not specify which reactor did the conversion. Huang and Xi addressed the conversion work of Plant 821 without mentioning the conversion of Reactor 801 conversion. Huang and Xi, "The Status of China's Production Reactor," *op. cit.* Thus, these publications indicate that the Guangyuan reactor could have started the conversion work in 1984.

143. See, for example, "China's Plutonium and Tritium Production," *op. cit.* Some accounts mentioned the safety concerns about the dual use of the plutonium-production reactors. These concerns were generated by the accident in April 1986 at the Chernobyl reactor, which was also a graphite-moderated reactor.

144. This is consistent with Zheng's description of Reactor 821 that the last stage of the reactor operation was from 1981 to 1986, based on his reading of the history of plant, *"Plant 821 (1969–1987)."*

145. Zuo Xiaojun, a blog of recollections of the author's father, who worked at Plant 821, a blog at CNNC Sichuan Environmental Protection Engineering Co., Ltd. , July 20, 2011, www.zh821.com/Retired-Show.aspx?id=1224 (in Chinese). This statement is consistent with a report that Plant 404 was required to "close the reactor and stop reprocessing" in August 1987 as well at a State Council meeting See, for example, "The 50th Anniversary Celebration of the Plant 404," *op. cit.*

146. The fact that Plant 821 released in 1988 the first volume of its history Plant 821 (1969–1987) may support such a belief.

147. The company declared bankruptcy in 2009. See "The Liquidation Work of Wuzhou Company Bankruptcy Is Almost Over," *CNNC News,* 16 April 2010. www.cnnc.com.cn/publish/portal0/tab283/info47848.htm (in Chinese).

148. See the blog of Zuo Xiaojun, *op.cit.*

149. See, for example "The Days of Racing to Complete Plant 821," *op.cit.*

150. As in the case of the Jiuquan reactor, the reactor is assumed to have produced 0.9 g/MWd for the entire period of its operation.

151. As with the Jiuquan reactor, under the government policy on fissile-material reduction in 1980s and the HEU production cases, Reactor 821 could have reduced production significantly during the 1980s before it shut down. It is assumed the production rate of the reactor fell on average around 50 percent during 1980–1984. At a reduction rate of 25 percent or 75 percent, it could create an uncertainty of about 7 percent in the total plutonium produced in China.

152. See, for example, *Dictionary of World Excellent Experts, op. cit.;* See also "China's Plutonium and Tritium Production," *op. cit.*

153. This assumes that China used its plutonium-production reactors to produce most of the tritium for its nuclear-weapon arsenal from 1967 to 1987 and that most of China's nuclear weapons during the given period are two-stage thermonuclear weapons. However, it is not sure how many of those warheads use tritium to boost its primaries. China tested its hydrogen bomb in 1966 and closed its reactors in 1986. The annual tritium requirement in year t is determined by the total tritium requirement for new added weapons from year t-1 (that is, one year before year t), and the tritium requirement to make up for the decay in year t. Using data from the Federation of American Scientists on the evolution of China's nuclear arsenal and assuming each warhead needs about 4–8 grams of tritium, it is estimated the total tritium requirement for China's arsenal from 1967 to 1987 could be about 1.7–3.3 kg. See Hans M. Kristensen and Robert S. Norris, "Global Nuclear Weapons Inventories, 1945–2013,"*Bulletin of the Atomic Scientists",* vol. 69, Issue 5, 2013. In addition, China conducted about seven thermonuclear tests during the period. See, for example, Nuclear Threat Initiative, "China's Nuclear Tests: Dates, Yields, Types, Methods, and Comments," *op. cit.* Thus, testing may have consumed an additional 30–60 grams of tritium. The production of one kilogram of tritium reduce a reactor's plutonium production by about 72 kg, cf. Thomas B. Cochran et al., *Nuclear Weapons Databook. Vol. 2, U.S. Nuclear Warhead Production* (Cambridge, MA:Ballinger, 1987), p. 180, footnote 4. Consequently, the tritium production by plutonium-production reactors could reduce the amount of plutonium about 120–240 kg. It is not clear if China used other means to produce tritium for weapons during the period. However, those changes could be insignificant, given that the total plutonium reduction by tritium could account for only around 5 percent of the total plutonium produced, which would be within the uncertainty as given here.

154. This is significantly higher than the 1.6 to 2.4 tons that ISIS recently estimated as the total amount of plutonium produced in China. See Albright and Kelleher-Vergantini, *Military Highly Enriched Uranium and Plutonium Stocks in Acknowledged Nuclear Weapon States, op. cit.* One major reason for the lower estimate is that the assumed reactor power is much less than what the newly available information indicates it is. Another reason is that the capacity factors that the ISIS authors assume is much lower. For instance, they assume the upper bound of the capacity factor until 1980 is about 60 percent. However, as *China Today* reported, one major improvement to increase plutonium production during 1976–1980 was to increase the number of reactor operation days per year from the original 288 to 324, representing an increase in the capacity factor from about 79 percent to 89 percent. See Li et al., eds., *China Today: Nuclear Industry, op. cit.,* p. 214.

155. Diakov, "The History of Plutonium Production in Russia," *op. cit.*

156. See Zheng "Something Can be Spoken – the Original Secrets of Nuclear Industry," *op. cit.*

157. NNSA, *Annual Report 2006, op. cit.*

158. Communication by the author with Chinese nuclear experts, spring 2013.

159. Diakov, "The History of Plutonium Production in Russia," *op. cit.*

160. This is halfway between the 6 kg used in the first U.S. plutonium nuclear weapons and the 4 kg assumed for the pits of modern nuclear weapons.

161. Gertz and Scarborough, "A Nation Inside the Ring," *op. cit.*; Norris and Arkin, "World Plutonium Inventories," *op. cit.*

162. Albright and Kelleher-Vergantini, *Military Highly Enriched Uranium and Plutonium Stocks in Acknowledged Nuclear Weapon States, op. cit.*

163. More can be found at CCTV-10 interviews and discussions with experts and former soldiers involved in Project 816, http://tv.cntv.cn/video/C24886/d393d975879c40a01e674083c59c91f5 (in Chinese). See also "Nuclear Reaction to Tourist Attraction," *op. cit.;* and "Former Nuclear Plant Opening as Tourist Attraction," *China Daily,* 13 April 2010, www.chinadaily.com.cn/china/2010-04/13/content_9719335.htm.

164. Communication by the author with CNNC experts, Suzhou, China, November 2016. While the Jiuquan reactor was designed for dual use, it was not built that way from the beginning. Li et al., eds., *China Today, Nuclear Industry, op. cit.,* p. 86.

165. A blog "The Underground Plant 816 at Chongqing," http://blog.sina.com.cn/s/blog_5a53af350100aqzk.html (in Chinese).

166. More details on the history of Plant 827 can be read in Ren Dexi, "My Dream of China's Nuclear Industry-II," *Journal of University of South China,* no. 4, 2014, http://nhdxb.cuepa.cn/show_more.php?doc_id=1126826 (in Chinese); Ren Dexi, "My Dream of China's Nuclear Industry-III," *Journal of University of South China* (in Chinese), no. 7, 2014. The author of these articles was a senior engineer at plant 827. He left the plant in 1982 when the plant was coming to be closed and became a professor at University of South China, http://nhdxb.cuepa.cn/show_more.php?doc_id=1042791 (in Chinese). Ren referred to the two planned reactors as "one modern production reactor and one heavy-water power reactor," but he did not mention specifically whether the "advanced production reactor" was for plutonium or tritium or both. However, another resource specified that the production reactor was a military heavy-water tritium-production reactor. See, for example, *Dictionary of World Excellent Experts, op. cit.*

167. Ren, "My Dream of China's Nuclear Industry-II," *op. cit.*

168. See, for example, Jeffrey Lewis, "The Untold Story of China's Forgotten Underground Nuclear Reactor," Foreign Policy, 8 July 2014, http://foreignpolicy.com/2014/07/08/the-untold-story-of-chinas-forgotten-underground-nuclear-reactor/.

169. See, for example, *Dictionary of World Excellent Experts, op. cit.* In the introduction by Song Yunzhi, a senior engineer, the dictionary emphasized that Song received national awards due to his major contribution to using Reactor 801 for mass production of tritium and saved investment of 0.5–0.8 billion yuan for the military heavy-water tritium-production reactor ("JunYong Zhongshui Chanchuan Dui" as described in the dictionary) of Project 827.

170. Ren "My Dream of China's Nuclear Industry-II," *op. cit.;* Li et al., eds., *China Today: Nuclear Industry, op. cit.*, p. 312.

171. This assumes that one 1 GWe Candu reactor could produce annually about 180 g of tritium. See *Banning the Production of Highly Enriched Uranium, op. cit*. One 137 MWe heavy-water reactor could produce about 25 g of tritium, which could replace the decay loss of an arsenal of 56–112 thermonuclear warheads (assuming 4–8 g for each warhead). It has been reported that China increased its arsenal from 36 in 1970 to 116 in 1973. See Kristensen and Norris, "Global Nuclear Weapons Inventories, 1945–2013," *op. cit.*

172. See, for example, "The Third-line Constructions in Yichang – Some Data on Project 827." http://our827.blog.163.com/blog/static/6294867520098121810683/ (in Chinese).

173. Ren, "My Dream of China's Nuclear Industry-II," *op. cit.*

174. The pilot civilian reprocessing plant at Plant 404, commissioned in 2010, was based in part on research conducted at Project 827. See, for example, China Academy of Engineering, *Re-examining China's Nuclear Energy Development* (Beijing: Tsinghua University Press, 2015), p. 327.

175. Ren, "My Dream of China's Nuclear Industry-II," *op. cit.*; "The Third-line Constructions in Yichang – Some Data on Project 827," *op. cit.*

176. See Zheng Jiye, Luo Zhiwen, and Liu Hongwein, "Study on the Decommissioning of the Heavy-Water Zero-Power Reactor," *Proceedings of National Workshop on Decommissioning Plans of Nuclear and Radiation Facilities,* Chinese Nuclear Association, 1 November 2007, Mianyang, Sichuan. http://cpfd.cnki.com.cn/Article/CPFDTOTAL-EGVD200711003063.htm (in Chinese).

177. Li Maoji, et al., "Heavy Water Lattice Experiments on HEU Fueled HWZPR," "*Atomic Energy Science and Technology,*" 1984, No. 6 (in Chinese).

178. Zheng, Luo, and Liu, "Study on the Decommissioning of the Heavy-Water Zero-Power Reactor," *op.cit.*

179. One of the two proposed heavy-water reactors was intended for electricity generation. After the Gezhou Dam was built, the need for such a reactor in the region was not as urgent. Meanwhile, China selected a PWR design for its Qinshan-1 power reactor, reducing the importance of the heavy-water power-reactor project. China also was able to produce tritium in its plutonium-production reactor, further reducing the importance of the heavy-water reactors. All these developments may have contributed to the slow progress of Project 827, and why it was abandoned.

180. More details can be found in Wang Kebin, "Base 200 and Project 820 in the Great Cultural Revolution," 20 November, 2015, http://wang-kebin.hxwk.org/ 2015/11/20/%E6%96%87%E9%9D%A9%E4%B8%AD%E7%9A%84200%E5%8F%B7%E5%92%8C820%E5%B7%A5%E7%A8%8B/(in Chinese). See also Cui, "The Life of Sanbei," *op. cit.*

181. Wang, "Base 200 and Project 820 in the Great Culture Revolution," *op. cit.*

182. *Ibid.*

183. Bunn, Zhang, and Kang "The Cost of Reprocessing in China," *op. cit.*

184. IAEA, "Communication Received from China Concerning Its Policies Regarding the Management of Plutonium," *op. cit.*

185. Zhang Donghui, "Status of China's National SFR Program," presentation at International Workshop on Prevention and Mitigation of Severe Accidents in Sodium-Cooled Fast Reactors, Tsuruga, Japan, 12–13 June 2012.

186. Yue Qi, "China Establishes Its First National Nuclear Technology Industrial Park and Begins Industrialization of Spent Fuel Reprocessing in Gansu," *National Business Daily,* 25 August 2015, http://www.nbd.com.cn/articles/2015-08-25/940911.html (in Chinese).

187. Chris Buckley, "Thousands in Eastern Chinese City Protest Nuclear Waste Project," *New York Times*, 8 August 2016, https://www.nytimes.com/2016/08/09/world/asia/china-nuclear-waste-protest-lianyungang.html?_r=0.

188. IAEA, "China Experimental Fast Reactor," *Power Reactor Information System,* http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=1047.

189. "China Experimental Fast Reactor Runs at Full Capacity," *Xinhua News,* 19 December 2014, http://www.cs.com.cn/english/ei/201412/t20141219_4595461.html.

190. Communication by the author with CNNC experts, Beijing, China, November 2016.

191. Yang Hongyi, "Economic Issues of Fast Reactor in China," presentation at Technical Meeting on Fast Reactors and Related Fuel Cycle Facilities with Improved Economic Characteristics, Vienna, Austria, 11–13 September 2013, https://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-09-11-09-13-TM-NPTD/7.yang.pdf; Wan Gang, "An Authoritative Interpretation on China's FBR Development," 14 March 2014, http://www.ns.org.cn/c/cn/news/2014-03/14/news_1138.html.

192. Yang, "Economic Issues of Fast Reactor in China," *op. cit.*

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