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China's HEU and Plutonium Production and Stocks

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This article discusses the history of China's production of highly enriched uranium and plutonium for nuclear weapons and uses new public information to estimate the amount of highly enriched uranium and plutonium China produced at its two gaseous diffusion plants and two plutonium production complexes. The new estimates in this article are that China produced 20 ± 4 tons of HEU, 2 ± 0.5 tons of plutonium, and currently has stockpiles of about 16 ± 4 tons of HEU and 1.8 ± 0.5 tons of plutonium available for weapons. The values for China's fissile material production are at the low end of most previous independent estimates, which range from 17–26 tons of highly enriched uranium and 2.1–6.6 tons of plutonium. These new estimates would be significant to assess China's willingness to join a fissile material cutoff treaty and a multilateral nuclear disarmament.

China launched its nuclear-weapon program in the mid 1950s. Initially, with assistance from the Soviet Union, China began to construct fissile-material production facilities in the late 1950s. Highly enriched uranium (HEU) production began in 1964 and plutonium production in 1966. In the late 1960s, China began to construct a second set of plutonium and HEU production facilities in Southwest China, far from the coast and border with the Soviet Union, which came into operation in the 1970s. This "Third Line" program was intended to provide China with backup facilities in case the first production facilities were destroyed.

China has kept information about its stocks of fissile materials and nuclear weapons secret. While China has not declared officially that it has ended HEU and plutonium production for weapons, it is believed to have done so after Beijing began to give priority to its economic and political reforms in 1978.

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Table 1: Operating history of China's military fissile-material-production facilities.

Facility	Start up	Shutdown
Enrichment plants		
Lanzhou gaseous diffusion plant	1964	Stopped HEU production in 1979
Heping gaseous diffusion plant	1975	Stopped HEU production in 1987
Plutonium production Reactors		
Jiuquan reactor	1966	Shutdown in 1984
Guangyuan reactor	1973	Shutdown in 1989?
Reprocessing facilities		
Jiuquan intermediate pilot plant	1968	Shutdown in early 1970s
Jiuquan reprocessing plant	1970	Shutdown around 1984
Guangyuan reprocessing plant	1976	Shutdown around 1990

China moved to reduce military HEU and plutonium production, switching some facilities to civilian purposes and closing others, finally stopping production of HEU in 1987 and of plutonium by about 1990.

Table 1 summarizes the start-up and shut-down dates for China's military uranium enrichment and plutonium production facilities.

Without knowledge of the operating history and power of China's plutonium-production reactors and the capacities of its uranium enrichment plants, any estimates of China's fissile material stocks will have great uncertainties.

Based on new public information, the revised estimates in this article are that China produced 20 ± 4 tons of HEU, 2 ± 0.5 tons of plutonium and currently has stockpiles of about 16 ± 4 tons of HEU and 1.8 ± 0.5 tons of plutonium available for weapons.[1] The values for China's fissile material production are at the low end of most previous independent estimates, which range from 17–26 tons of HEU and 2.1–6.6 tons of plutonium.[2] The new plutonium estimate is consistent, however, with a U.S. Department of Energy assessment from 1999 that China had a stockpile of 1.7–2.8 tons of plutonium for weapons.[3]

HIGHLY ENRICHED URANIUM PRODUCTION AND INVENTORY

China has produced HEU for weapons in two complexes:

- The Lanzhou gaseous diffusion plant (Plant 504)
- The Heping gaseous diffusion plant (Plant 814), a "Third Line" facility.

China also used these enrichment plants to produce HEU for its research reactors and low-enriched uranium (LEU) for naval reactors. Today, China operates two centrifuge enrichment plants at Hanzhong (Shaanxi province), and at Lanzhou (Gansu province) to produce LEU for civilian purposes.[4]

Lanzhou Gaseous Diffusion Plant

In 1958, with help from the Soviet Union, China started the construction of a gaseous diffusion plant on a bank of the Yellow River in Lanzhou, in Gansu province (Figure 1). Two years later, the Soviet Union withdrew its technical experts.[5] The Lanzhou plant produced its first weapon-grade HEU in January 1964 and, over the next few months, enough for China's first nuclear test in October 1964.

There were early efforts by the United States to assess the enrichment capacity of the Lanzhou plant using aerial and satellite imagery, but it proved to be difficult to make reliable estimates. The United States used the U-2 spy plane to photograph the Lanzhou site in September 1959.[6] Progress was revealed by further U-2 photos taken in March and June 1963. U.S. intelligence believed, however, that the processing building was large enough to contain only about 1800 compressor stages, substantially less than the 4000 stages required to produce weapon grade materials.[7] Moreover, the U.S. government worked on the presumption that plutonium, not uranium, would be the fissile material in China's first bomb.[8] It was therefore a surprise when analysis of residues in the atmosphere from China's first nuclear explosion identified it as

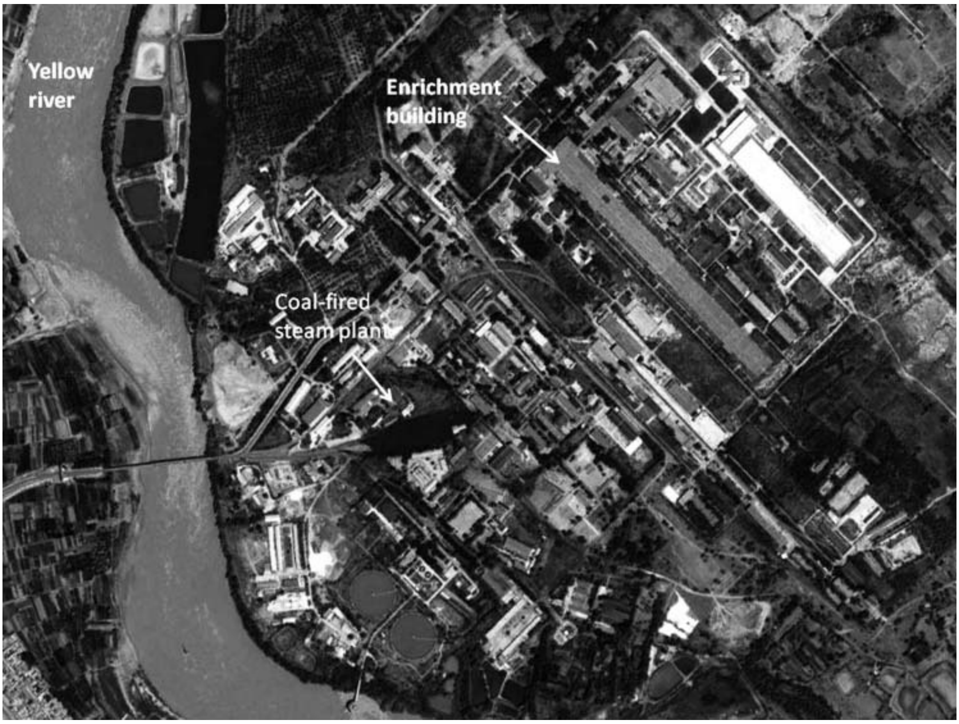

Figure 1: Lanzhou gaseous diffusion plant. Satellite image from 5 July 2004 (Coordinates: 36° 09′2.68″N/103° 31′06.35″E). Source: DigitalGlobe and Google Earth.

an HEU-based bomb.[9] In December 1964, a U-2 flight equipped with infrared detection systems confirmed that the Lanzhou plant was indeed operating.[10]

In 1972, the U.S. Defense Intelligence Agency (DIA) estimated that Lanzhou was producing 150–330 kg per year of HEU.[11] This production rate is equivalent to 24,000–53,000 separative work units (SWU) per year at a tails assay of 0.5 percent, or 30,000–66,000 SWU per year for 0.3 percent tails.[12]

China's official nuclear history notes that the capacity of the Lanzhou facility was increased after it started operating, aided by the use of a new type of separation membrane.[13] Chinese media reports suggest the design capacity of the Lanzhou plant doubled by the end of the 1970s.[14] Western sources indicate Lanzhou had achieved a capacity of 180,000 SWU per year by 1978.[15]

In 1978, China adopted a policy of economic reform. As part of this shift, it appears that in 1980, Lanzhou stopped production of HEU and shifted to making LEU for civilian power reactors.[16] In 1981, China began to supply LEU for the international market.[17] Previous estimates of China's HEU production generally have assumed the Lanzhou plant stopped HEU production for weapons in 1987.

Enrichment capacity at Lanzhou increased further during the 1980s and it was reported in 1989 that the plant was operating at a capacity of about 300,000 SWU per year.[18] In 1998, however, the decision was made to decommission the Lanzhou facility as part of a project aimed at replacing China's gaseous diffusion technology with centrifuge enrichment.[19] A new centrifuge enrichment facility provided by Russia with a capacity of 0.5 million SWU per year began operation in 2001. By agreement with Russia, this plant produces only LEU for non-weapons purposes.[20]

Based on the above information, the following assumptions are made concerning the historical development of HEU production at the Lanzhou gaseous diffusion plant:

- From 1964–65, about 20,000 SWU/yr at a tails assay of 0.5 percent;
- From 1966–70, a linear increase from to 50,000 SWU/yr at a tails assay of 0.5 percent;[21]
- From 1971–75, a linear increase to 90,000 SWU/yr at a tails assay of 0.3 percent; and
- From 1976–79, a linear increase from 90,000 to 180,000 SWU per year at a tails assay of 0.3 percent
- HEU production stopped in 1980 and the plant produced LEU from 1980 until 1987, when it ended operations

Based on the above information, it is estimated that operating continuously at full capacity up to 1980, the Lanzhou plant would have produced 1.1

million SWU. This would be sufficient to produce about 6 tons of weapon-grade (90 percent enriched) HEU. It is assumed that thereafter, the Lanzhou plant produced LEU until 1987, when it ended operations.

Heping Gaseous Diffusion Plant

China built its second gaseous diffusion plant as part of its "Third Line" defense program. The Heping facility (also known as Plant 814) is located in the Heping Yizu area of Jinkouhe, in Sichuan province. It is believed to have started operating around 1975 and stopped HEU production in 1987.[22] In the late 1980s, based on China's "military-to-civilian conversion" policy, this plant was converted to other purposes, including fluorine production.

Given the paucity of public information available about this plant, there is little basis for more than a rough estimate of its HEU production. Based on satellite imagery the Heping plant had a slightly larger processing building than that of the Lanzhou facility. It is assumed that the original capacity of the Heping plant was not significantly larger than that of the Lanzhou plant in 1975, i.e., about 90,000 SWU per year.[23] This reflects the fact that, when Beijing decided to build the "Third Line" fissile material production facilities, its first production facilities were just coming into operation and there was no reason for Beijing to build significantly larger backup facilities than those that were being backed up.[24] It also is assumed that, like the Lanzhou plant, the Heping plant roughly doubled its capacity by the end of the 1970s. This is consistent with a report that the output of the Heping plant before it shut down was 200,000–250,000 SWU per year.[25]

The following history is therefore assumed for the capacity of the Heping plant:

- From 1975–79, a linear increase from 100,000 to 230,000 SWU per year at a tails assay of 0.3 percent
- From 1980–87 the plant operated at 230,000 SWU per year at a tails assay of 0.3 percent
- In 1987, the plant ended HEU production.

In this scenario, operating continuously at full capacity up to 1987 the Heping plant would have produced 2.7 million SWU, sufficient to produce about 14 tons of HEU.

Together, the Lanzhou and Heping gaseous diffusion plants therefore would have produced roughly 3.8 million SWU, enough to make about 20 tons of weapon-grade HEU (see Figures 2 and 3). This estimate assumes that China used only natural uranium feed for its enrichment program. It is possible that some of China's HEU was produced from reprocessed uranium recovered

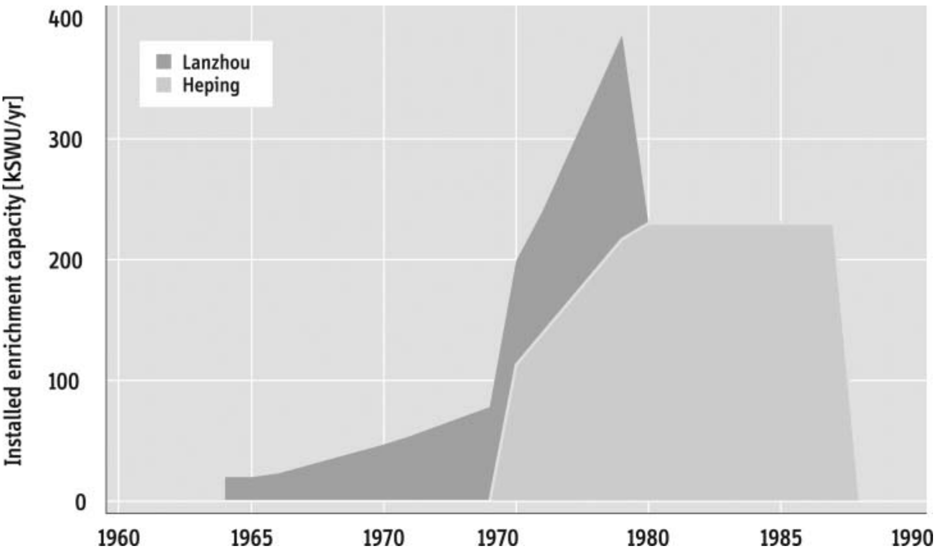

Figure 2: Reconstructed history of total enrichment work done by the Lanzhou and Heping GDPs during the periods when they were producing HEU (thousands of SWU/yr).

from its plutonium production reactors.[26] Enriching reprocessed uranium, which contains less uranium-235 than natural uranium, would have required more SWUs per kilogram of HEU produced but the effect would not have been large.[27]

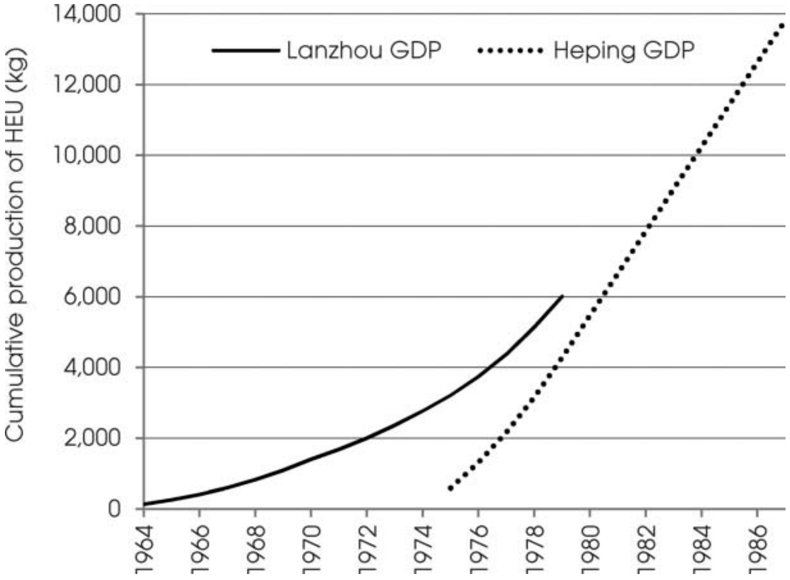

Figure 3: Cumulative production of HEU at Lanzhou and Heping GDPs.

In addition to producing HEU for nuclear-weapons, China's gaseous diffusion plants also would have supplied enriched uranium for research and naval reactors.

Research Reactor Fuel

China has had two HEU-fueled research reactors: the 125 megawatt thermal (MWt) High Flux Experimental and Test Reactor (HFETR); and the 5 MWt Min Jiang Test Reactor (MJTR).[28] The HFETR reached criticality in 1979 and converted to LEU fuel in 2007. The MJTR reached criticality in 1991 and converted to LEU fuel in 2007. Before conversion, these two reactors would have together consumed about 1 ton of HEU.[29] This would correspond to about 200,000 SWU at a tails assay of 0.3 percent.

Russia has supplied China with some HEU fuel for research reactors.[30] China, as of 2003, was estimated to have about 1 ton of civil HEU enriched by itself and by Russia.[31] This amount of civil HEU would have been sufficient to supply China's research reactors. China's use of HEU for research reactors in the future may be insignificant.

China's Experimental Fast Reactor (CEFR), which reached criticality in July 2010, has a first loading of almost 240 kg of HEU (enriched to 64.4 percent uranium-235), provided by Russia.[32] The CEFR will use plutonium-uranium fuel in later loadings, as will China's planned future fast reactors.

Naval Reactor Fuel

China launched a nuclear-powered submarine program in 1958. Desiring that these submarines not compete with the nuclear-weapon program for HEU, China decided to use less than 5 percent enriched LEU fuel for its naval reactors.[33] A land-based prototype reactor began tests in May 1970, becoming fully operational in July 1970. The whole-life test of the reactor core ended in December 1979 and the spent fuel was discharged in 1981.[34]

China's first Type 091 *Han*-class nuclear-powered attack submarine entered service in 1974, and was retired in 2000. It is reported that China currently has four *Han*-class and two new Type 093 *Shang*-class nuclear-powered attack submarines in service.[35] The first nuclear-powered strategic ballistic missile submarine (SSBN, Type 092 *Xia*-class) was launched in 1982 and went on patrol in 1986. One *Xia*-class SSBN is operational today but it has never gone on patrol.[36]

Each of these submarines has one 90 MWt pressurized-water reactor.[37] If the reactor cores are designed to have life spans of 10 years, it is estimated that each fuel load of China's naval reactors would require about 2.3 tons of 5 percent LEU. [38] The Lanzhou and/or Heping plants would have needed to produce 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.[39] This would have reduced the SWU available for making HEU for weapons by about 170,000 SWUs at a tails assay of 0.3 percent.[40]

Altogether, China's two gaseous diffusion plants would have supplied roughly 360,000 SWU of enriched uranium for non-weapon purposes. This would have left an estimated 3.4 million SWU available for producing weapons HEU, sufficient to produce about 17 tons of weapon-grade HEU.

Losses and Uses of HEU Produced for Weapons

Some of the HEU produced for weapons was consumed in nuclear weapon tests and process losses.

Nuclear Tests

China conducted 45 nuclear-weapons tests.[41] The first seven were carried out before China had plutonium available for weapons and presumably all were HEU weapons, including the 3-megaton thermonuclear weapon test in June 1967. About 200 kg of weapon-grade uranium could have been consumed in these seven tests.[42] In later tests China may have moved to more-compact plutonium-based pits for fission weapons and as primaries for two-stage thermonuclear weapons. Assuming that tests with yields significantly above 20 kT were thermonuclear weapons with secondaries containing weapon-grade HEU, then about 550 kg of HEU would have been consumed in these thermonuclear tests.[43] Altogether, nuclear weapons testing may have consumed about 750 kg of HEU or the equivalent of 0.15 million SWU.

Process Losses

We assume process losses of about 1 percent, somewhat larger than those reported for the U.S. uranium enrichment program. In this case, about 200 kg of weapon-grade uranium would have been lost during production.[44]

Other

China may have used tens of kilograms of HEU to fuel a tritium-production reactor—say 10,000 SWU.

A.Q. Khan has claimed that China provided 50 kg of weapon-grade HEU to Pakistan in 1982.[45] But many Chinese experts doubt this. Table 2 summarizes the above estimates.

It is estimated that China could have a current inventory of about 16 ± 4 tons of HEU for weapons.[46] This is at the low end of previous estimates.[47]

Table 2: China's estimated production and use of enrichment work.

Activity	Millions of SWUs produced or consumed
Enrichment work produced during the period China was producing HEU	3.8
Enrichment work used for non-weapon purposes	
Research-reactor fuel	−0.2
Naval-reactor fuel	−0.17
Tritium-production-reactor fuel	−0.01
Process losses	0.04
Nuclear tests	−0.15
Provided to Pakistan?	−0.01
Total remaining available for weapons HEU	3.2

PLUTONIUM PRODUCTION AND INVENTORY

China has produced plutonium for weapons at two sites:

1) Jiuquan Atomic Energy Complex (also referred to as Plant 404) near Yumen in Gansu province. This site includes China's first plutonium reactor and the associated reprocessing facilities.
2) Guangyuan plutonium production complex (Plant 821), located at Guangyuan in Sichuan province. This "Third Line" site includes a plutonium reactor and reprocessing facility.

It is believed that production of plutonium for weapons has ended at both sites. China is interested, however, in reprocessing civilian power-reactor fuel and has built a pilot commercial reprocessing plant. As of late 2010, the facility had not started normal operation.

Jiuquan Complex

The Jiuquan plutonium production reactor is a graphite-moderated, water-cooled reactor (see Figure 4). It was designed in 1958 with Soviet assistance and construction started in March 1960. China had not, however, received the key components of the reactor when the Soviet Union ended its support in August 1960.[48] Completion of the reactor project was significantly delayed as Beijing decided to concentrate on completing the Lanzhou enrichment plant. Work resumed on the Jiuquan reactor after the enrichment plant went into operation in 1964. The reactor went critical in October 1966 and went into full operation in 1967.[49]

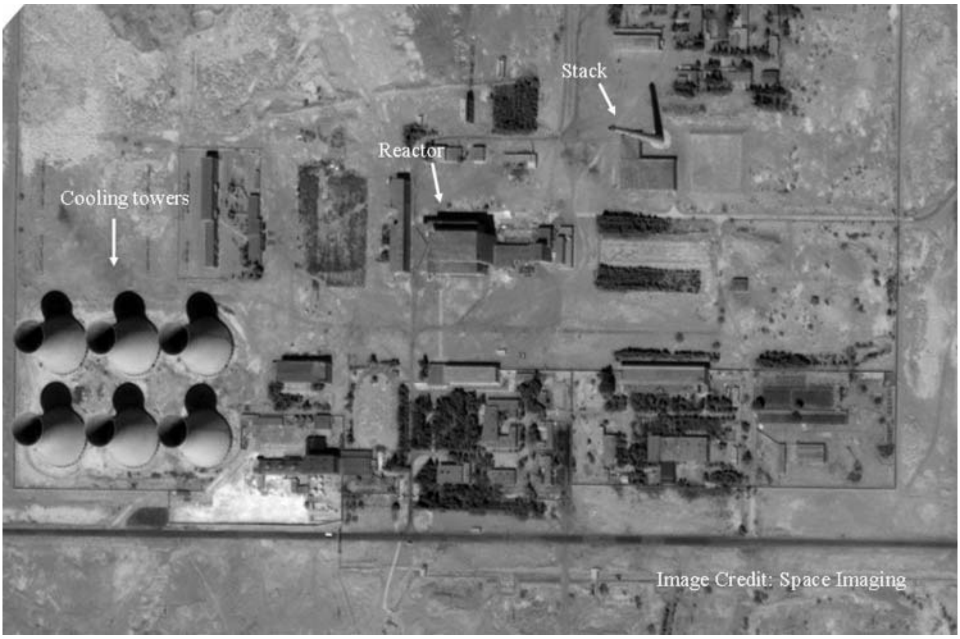

Figure 4: The Jiuquan plutonium production reactor. The image is from 25 February 2004. (Coordinate: 40° 13′23.32″N/97°21′21.26″ E). Source: Space Imaging.

During its early years, the reactor encountered a number of technical problems and was frequently shutdown. During the late 1960s and early 1970s, its operation also was affected by the political turmoil of the Cultural Revolution.[50] After 1970, however, the reactor ran without an unscheduled shutdown until it was shut down in 1974 for most of the year for tests, repair, and maintenance.[51]

The reactor reached its design power by the first half of 1975.[52] Thereafter, the power and performance of the reactor were increased significantly.[53] As a result of these improvements, by the end of 1970s, the plutonium production rate had increased 20 percent (realizing the "1.2 reactor" goal).[54] The reactor was most likely shut down in 1984.[55]

Construction of a pilot reprocessing plant near the reactor site started in 1965 and the plant began operation in September 1968. The plant had two production lines that could together process 0.4 tons of spent fuel per day and operated over 250 days a year.[56] This capacity could separate about 70 kg of weapon-grade plutonium per year.[57] It separated the plutonium for China's first test of a plutonium-based weapon, which occurred in December 1968.[58] The pilot reprocessing plant stopped plutonium separation when a larger plant, also built near the reactor site, began operating in April 1970.

Power of the Reactor

One approach to estimating the Jiuquan reactor's power is through the size of its six cooling towers. Based on commercial satellite images, it appears that that the towers have a top diameter of about 30 meters, which suggests a design power of about 14–140 MWt per tower.[59] Assuming that 85 percent of the heat was dissipated through the cooling towers and that two towers were kept on standby, the reactor power would be between 70 MWt and 660 MWt.[60] Thus, the cooling tower sizes do not provide the basis of an accurate estimate but do, at least, provide a consistency check for other estimates.

Since Russia helped design the Jiuquan reactor in the late 1950s, the power of Russia's graphite-moderated plutonium production reactors at Mayak at that time may be relevant. Russia's first production reactor, the *A* reactor, had an initial design thermal power of 100 MWt and, in the period between 1950–54 was operating at about 180 MWt, while subsequent reactors at Mayak were designed with a capacity of 300 MWt.[61] This suggests China's Jiuquan reactor could have had an initial design power in the range of 200–300 MWt.

Newly declassified information about the unfinished Chinese plutonium-production reactors (Plant 816) at Fuling, in Sichuan province, also provides a way to constrain estimates of the power of the Jiuquan reactor. Beijing decided in 1966 to build three 80 MWt graphite-moderated, water-cooled plutonium-production reactors and associated reprocessing facilities in caves under a mountain near Fuling as a "Third Line" project.[62] If the goal of the project was to build a back-up capacity to the Jiuquan reactor, the planned total power of 240 MWt at the new site probably matched that of the Jiuquan reactor.

Construction started on the Fuling reactors in February 1967. In 1969, given the very slow progress of the work in the mined-out caverns and increasing tensions with the Soviet Union, Beijing decided to meet its urgent need to have a backup for the Jiuquan complex by quickly building a plutonium-production complex at Guangyuan. In 1984, with the Guangyuan reactor operating, and a more benign international security situation, Beijing decided to end the Project 816 project at Fuling. By then about 85 percent of the civil engineering work had been finished and over 60 percent of the plant equipment had been installed. None of the reactors were ever loaded with fuel, however. The plant was converted to fertilizer production, the project was declassified in 2003 and part of the site was opened as a domestic tourist attraction in 2010 (Figures 5).

Plutonium Production

The plutonium production rate is dependent on the thermal power of the reactor, its capacity factor, and the amount of plutonium produced per megawatt-day of operation.[63] The estimated total plutonium production by

Figure 5: Left: Entrance to the Fuling nuclear complex. The sign in Chinese above the tunnel reads, "816 Underground Nuclear Project." Source: <http://news.qq.com/a/20100426/000373.htm)
Right: Project 816 reactor control room. This image shows core arrangements for three reactors—two to the left and one to the right of the circular display. Source: <http://news.qq.com/a/20100426/000373_3.htm>

the Jiuquan reactor is based on the above information and the following assumptions:

- From 1967 through June 1975, the reactor power increased linearly from 0.5 percent of design power to full design power, assumed to be 250 MWt. The capacity factor during 1967–69 is assumed to be 40 percent and thereafter about 80 percent (288 days per year) except for 1974, during which the reactor was mostly down for maintenance
- From July 1975 through 1979, the reactor linearly increased its plutonium production rate to 1.2 times, as reported for the end of 1979
- From 1980 until shutdown in 1984, the plutonium production rate stayed at 1.2 times the design rate.

Under these assumptions, the Jiuquan reactor could have produced a total of 1050 GWt-days of fission energy and generated a total of about 0.9 tons of weapon-grade plutonium.[64]

Guangyuan Complex

As already noted, in 1968, given the slow pace of work on the underground reactor complex at Fuling, Beijing decided to build an alternative "Third Line" plutonium production complex, Plant 821 at Guangyuan, also in Sichuan province. Like the Jiuquan reactor, the Guangyuan reactor was graphite moderated and water cooled and presumably of the same design power (see Figure 6).

Construction started in 1969, and the reactor achieved criticality in December 1973 and design power by October 1974.[65] By increasing the power

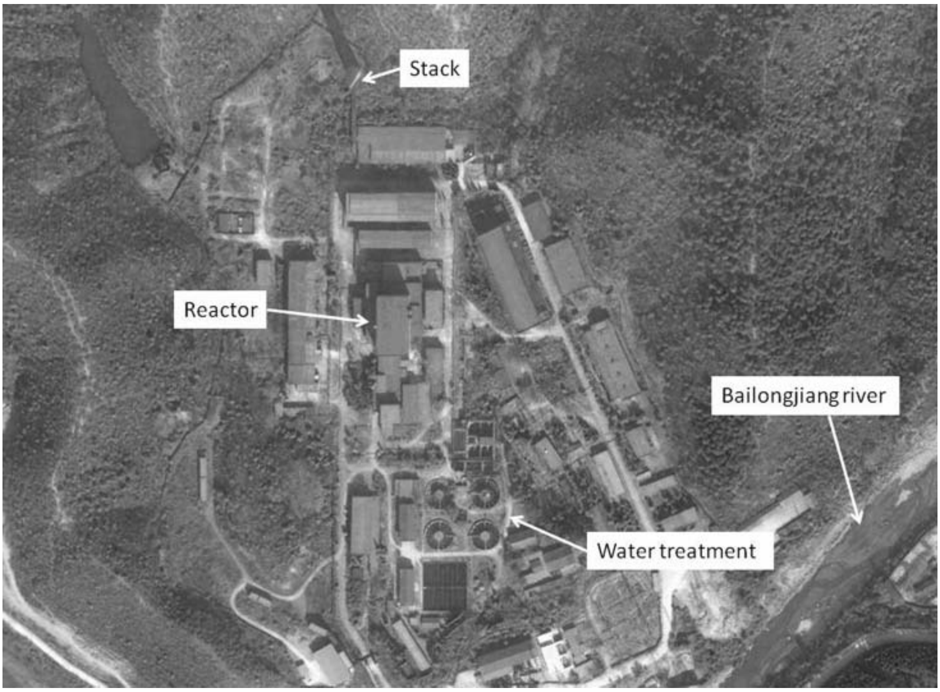

Figure 6: The Guangyuan reactor site. This image was taken on 31 August 2007 by a DigitalGlobe satellite (coordinates: 32° 29′ 44.27″ N/105° 35′ 24.48″ E) Source: DigitalGlobe and Google Earth.

and uranium-235 burnup, the plutonium production rate of this reactor was increased 30 percent by 1978, resulting in it being dubbed the "1.3 reactor."[66] Thus, combined with Jiuquan's "1.2 reactor," the Jiuquan and Guangyuan reactors were described as "2.5 reactors" by the end of the 1970s.[67] This description reinforces the assumption that the Jiuquan and Guangyuan reactors had similar design power.

It is reasonable to assume that the Guangyuan plant stopped plutonium production by 1989, when, following the new policy of "military-to-civilian conversion," the plant began to convert to civilian use, including aluminum manufacture.[68] The Guangyuan plant was reportedly shut down by 1991.[69] The complex is being decommissioned.

The reprocessing plant at the complex started operation in 1976 and reached its design capacity in 1977.[70] It presumably closed in the early 1990s after the last batch of fuel from the reactor had been reprocessed.

Plutonium Production

The estimated plutonium production by the Guangyuan reactor is based on the above information and the following assumptions:

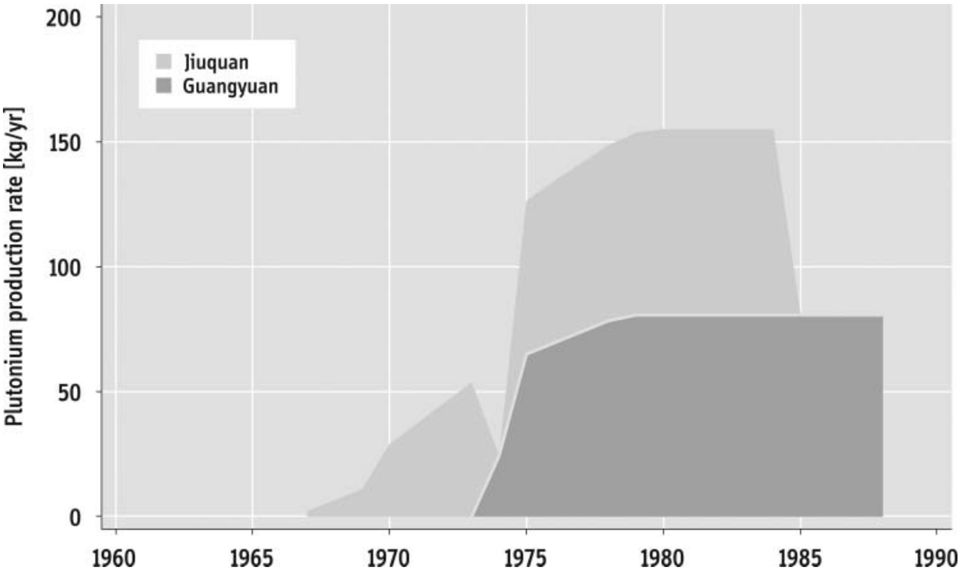

Figure 7: Reconstructed history of total production of weapon-grade plutonium by Jiuquan and Guangyuan reactors (kilograms per year).

- From December 1973 through October 1974, the reactor power increased to its design power of 250 MWt with a capacity factor of 40 percent
- From November 1974 through December 1978, the plutonium production rate increased linearly to 1.3 times the design rate of the Jiuquan reactor
- The reactor maintained this 1.3 times production rate until 1988. It is assumed the reactor stopped plutonium production at the end of 1988.

Under these assumptions, the Guangyuan reactor could have produced a total of 1,300 GWd and generated a total of about 1.1 tons of weapon-grade plutonium (see Figures 7 and 8).[71]

Use in Nuclear Tests

China carried out 38 nuclear tests after it began producing plutonium. Most of these tests could have contained weapon-grade plutonium, either in a simple fission weapon, a compact boosted fission weapon, or as the fission primary in a two-stage thermonuclear weapon. A total of about 200 kilograms of plutonium would have been used in these tests, assuming an average of 5 kg of weapon-grade plutonium per test.[72]

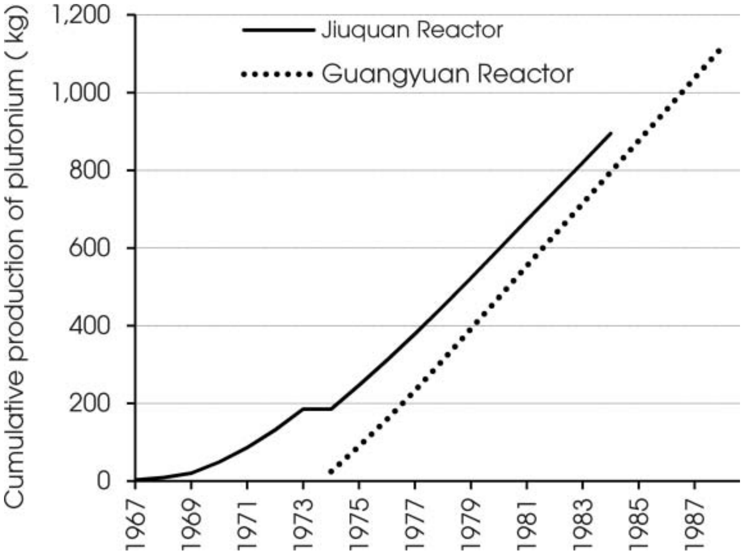

Figure 8: Cumulative production of weapon-grade plutonium at Jiuquan and Guangyuan reactors.

Plutonium Inventory

Thus, China's two plutonium production reactors produced an estimated 2 ± 0.5 tons of weapon-grade plutonium.[73] Subtracting the 200 kg of plutonium estimated to have been consumed in China's nuclear tests, its current inventory of weapon-grade plutonium would be 1.8 ± 0.5 tons.

This estimate is at the low end of a U.S. Department of Energy estimated range, reported in 1999, of 1.7–2.8 tons of weapon plutonium,[74] and smaller than most previous non-governmental estimates. It is smaller due largely to the assumption that the Jiuquan reactor and Guangyuan reactors had a design power of 250 MWt, whereas earlier estimates assumed that the Guangyuan reactor had a power twice that of the Jiuquan reactor. Earlier estimates also assumed that the power of these reactors increased much more than the 20–30 percent cited here.[75] The resulting decrease in estimated plutonium production due to the lower reactor power levels assumed here is somewhat offset by the assumption of higher capacity factors.

China reports no inventory of separated civilian plutonium in its declaration to the International Atomic Energy Agency (IAEA), the most recent of which was for the end of 2007.[76] This situation can be expected to change soon, however. In 2010, China completed and began testing a pilot commercial reprocessing plant with a capacity of 60 tons of spent fuel per year. The China National Nuclear Corporation has also proposed building a commercial-scale reprocessing plant with a capacity of 800 tons per year by 2025.[77] Such a plant could separate about 8 tons of plutonium per year. This would quickly provide

China with a civilian inventory of separated plutonium much larger than its military stockpile.

CONCLUSIONS

While China has not declared officially that it has ended HEU and plutonium production for weapons, based on new public information, it is believed that China stopped production of HEU in 1987 and of plutonium by about 1990. All its previous military production facilities have been closed, converted, or are being decommissioned.

Based on new public information, this article estimates that China produced 20 ± 4 tons of HEU, 2 ± 0.5 tons of plutonium and currently has stockpiles of about 16 ± 4 tons of HEU and 1.8 ± 0.5 tons of plutonium available for weapons. These new estimates are significantly lower than most previous independent estimates, which range from 17–26 tons of HEU and 2.1–6.6 tons of plutonium. The estimates presented here show that China could have the smallest military stockpile of HEU and plutonium available for weapons among the five acknowledge nuclear weapon states, which is consistent with China's minimum nuclear deterrence policy.

It should be noted that without the official knowledge of the operating history and power of China's plutonium-production reactors and the capacities of its uranium-enrichment plants, any estimates of China's fissile material stocks will have great uncertainties. However, the estimates and approaches described here would be used to further narrow the uncertainties as new information becomes available.

China's existing smaller stockpile of fissile material would be sufficient for its current modernization programs. However, if the United States moves its missile defense and space weapons plans forward, which would drive China to build more intercontinental ballistic missiles to neutralize those threats, China may need more fissile materials, thus retaining its option to restart production of fissile materials and be unwilling to join a fissile material cutoff treaty.

Moreover, China's limited stockpile of fissile materials would put a cap on its arsenal of weapons, which could influence China's decision on when China would join the process of the multilateral nuclear disarmament.

NOTES AND REFERENCES

1. China's highly enriched uranium is assumed to be 90 percent uranium-235 and weapon–grade plutonium is taken to be 94 percent plutonium-239.

2. For previous estimates of China's fissile material stocks, see, e.g., Robert S. Norris, A. S. Burrows, and R. W. Fieldhouse, *Nuclear Weapons Databook, Volume V*: *British, French, and Chinese Nuclear Weapons* (Washington, DC: Westview Press, 1994); David Albright, Frans Berkout, and William Walker, *Plutonium and Highly Enriched Uranium 1996* (New York: Oxford University Press, 1997); David Wright and

Lisbeth Gronlund, “Estimating China’s Production of Plutonium for Weapons,” *Science and Global Security* 11 (2003): 61; David Albright and Corey Hinderstein, “Chinese Military Plutonium and Highly Enriched Uranium Inventories,” *ISIS*, 30 June 2005. These estimates have drawn mainly on translations of China’s official nuclear history: Li Jue, Lei Rongtian, Li Yi, and Li Yingxiang, eds., *China Today: Nuclear Industry* (Beijing: China Social Science Press, 1987) (in Chinese). Selections were translated into English 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; and John W. Lewis and Litai Xue, *China Builds the Bomb (*Stanford, CA: Stanford University Press, 1988).

3. The U.S. Department of Energy (DOE) estimate was first reported in Bill Gertz and Rowan Scarborough, “A Nation Inside the Ring,” *The Washington Times*, 9 July 1999. A more detailed report appeared in Robert S. Norris and William M. Arkin, “World Plutonium Inventories,” *Bulletin of the Atomic Scientists,* (September/October 1999): p. 71. The U.S. Department of Energy estimate also assigned China a stockpile of 1.2 tons of civil plutonium.

4. It is reported that China is also operating its own demonstration CEP near Lanzhou. See, e.g. “China’s Indigenous Centrifuge Enrichment Plant,” *Uranium Intelligence Weekly*, Vol. IV, No. 43, October 25, 2010.

5. *China Today: Nuclear Industry*, *op. cit.* (in Chinese), p. 172. Subsequent references are to this Chinese version.

6. Director of Central Intelligence, Special National Intelligence Estimate (SNIE) 13-2-63, “Communist China’s Advanced Weapons Program,” 24 July 24 1963, National Security Archive. <http://www.nsarchive.org>.

7. “Summary and Appraisal of Latest Evidence on Chinese Communist Advanced Weapon Capabilities,” U.S. Arms Control and Disarmament Agency, ACDA-957, 10 July 1963. As of August 1964, U.S. intelligence agencies still believed the Lanzhou uranium enrichment plant was not complete. The U.S. Central Intelligence Agency (CIA) assumed that China would not have enough fissile material for a test until after the end of 1964. Director of Special Intelligence, “The Chances of an Imminent Communist Chinese Nuclear Explosion,” Special National Intelligence Estimate, 13-4-64, August 26, 1964, declassified version in Kevin Conley Ruffner (ed.), CIA Cold War Records Series*, Corona: America’s First Satellite Program* (Washington, D.C.: Center for the Study of Intelligence, 1995).

8. Joel Ullom, “Enriched Uranium versus Plutonium: Proliferant Preferences in the Choice of Fissile Material,” *Nonproliferation Review* 2 (1994): 1, 1–5. A reactor was detected at Baotou nuclear complex by a March 1963 U-2 flight. U.S. intelligence mistakenly believed that it was a production reactor with a thermal power around 30 MWt, able to produce plutonium for one or two bombs a year. They estimated that a likely date for China to test its first plutonium-based device would be late 1964 or early 1965. U.S. Arms Control and Disarmament Agency, *op. cit*.

9. William Burr and Jeffrey Richelson, “Whether to Strangle the Baby in the Cradle,” *International Security* 25 (2001/2001): 3, 91.

10. See, e.g. R.E. Lawrence and Harry W. Woo, “Infrared Imagery in Overhead Reconnaissance,” *Studies in Intelligence* 11 (1967): 2, 17–40.

11. U.S. Defense Intelligence Agency, “People’s Republic of China Nuclear Weapons Employment Policy and Strategy,” Report No. TCS-654775-72, Washington, D.C., March 1972. The Manhattan Project physicist Ralph Lapp used the early experience at the Oak Ridge Tenn. gaseous diffusion plant to estimate in 1971 that, at start-up, the Lanzhou plant may have produced about 130 kg per year of weapon-grade HEU and been able to double its annual production by 1966 as operators gained experience with

the enrichment process; Lapp projected that the production capacity could increase to over 350 kg per year of HEU by the 1970s, Charles Murphy, "Mainland China's Evolving Nuclear Deterrence," *Bulletin of the Atomic Scientists,* January 1972, pp. 28–35.

12. Albright and Hinderstein, *op. cit.* They assumed China's weapon-grade HEU was 93 percent uranium-235. If it is assumed to be 90 percent uranium-235, this production rate is equivalent to 23,000–51,000 SWU per year at a tails assay of 0.5 per cent, or 29,000–64,000 SWU per year for 0.3 per cent tails.

13. *China Today: Nuclear Industry, op. cit.*, p. 179.

14. Xie Wuzhan, "504 Chang: Gongheguo Nongsuoyou Shiyue de Lingpaozhe," *Gansu Ribao* (in Chinese) ("Plant 504: the leading runner of the cause of China's uranium enrichment," *Gansu Daily*) 31 May 2008.

15. "Mainland China Talking to French, Germans, about Nuclear Power," *Nucleonics Week*, 12 January 1978.

16. "Zhongguo Younongsuo ji Ranliao Yuanjian Zhizao ("China's Uranium Enrichment and Fuel Fabrication") 28 March 2009, <http://www.cnnuclear.cn/2009/0328/189.html>, and discussions with Chinese experts.

17. *China Today: Nuclear Industry, op. cit.*, p. 180.

18. Ann MacLachlan and Mark Hibbs, "China Stops Production of Military Fuel: All SWU Capacity Now for Civil Use," *Nuclear Fuel*, 13 November 1989.

19. Mark Hibbs, "China Said to be Preparing for Decommissioning Defense Plants," *Nuclear Fuel*, 17 May 1999.

20. It is not clear whether or not the contract also allows the production of LEU for naval-reactor fuel.

21. By leaving more of the uranium-235 in the tails (i.e., a tails assay of 0.5 percent rather than 0.3 percent), China could achieve a given HEU production rate with a lower enrichment capacity. This would require about twice the amount of natural uranium feed, however

22. Albright and Hinderstein, *op. cit.*

23. This assumed capacity is lower than the 1972 DIA estimate. In its 1972 estimate, the DIA estimated that this plant could produce 750–2950 kg of weapon-grade uranium per year. This would correspond to about 145,000–569,000 SWU per year at a tails assay of 0.3 per cent. Since this estimate was made several years before the plant was put into operation, it is not clear whether it was based on the existing building or on an assumption that the building would be expanded, U.S. Defense Intelligence Agency, *op. cit*.

24. It is noted below that the plutonium production reactor at Guangyuan, which was built as a third line facility, has the same design power as the original Jiuquan reactor that it was backing up.

25. See, e.g., "Zhongguo Younongsuo ji Ranliao Yuanjian Zhizao," *op. cit.*

26. China began in 1970 enriching uranium recovered from the irradiated fuel discharged from its plutonium production reactors. *China Today: Nuclear Industry, op. cit.,* p. 186.

27. Producing about 2 tons of plutonium (as discussed in the following section) would have resulted in about 4000 tons of reprocessed uranium. To enrich all of this uranium to 90 percent HEU, with a tails assay of 0.3 percent, would require about 3.2 million SWU. This is 154,000 SWU more than would be required to produce the same amount of HEU from natural uranium.

28. China also has about 4 Miniature Neutron Source Reactors (MNSR). Each requires a long-lived core containing about 1 kg of 90 percent HEU. One of them shut down in 2007 and China has decided to shut down the other three MNSRs and replace them with LEU-fueled neutron sources. In addition, China sold one MNSR each to Ghana, Iran, Nigeria, Pakistan, and Syria. China has a project to convert those reactors to LEU cores <http://www.nti.org/db/heu/china.html>.

29. Assuming that the 125 MWt HFETR had an average burnup of 40 percent of the urainuim-235 in its fuel and operated 12 weeks per year (IAEA research reactor database), and assuming 1.26 g of uranium-235 would be consumed per MWd (thermal) (Alexander Glaser, *Neutronics Calculations Relevant to the Conversion of Research Reactors to Low-Enriched Fuel*, Ph.D. Dissertation, Darmstadt, 2005) the HFETR would have used about 994 kg 90 percent HEU before conversion. The 5 MWt MJTR, with an average burnup of 45 percent and an operation of 14 weeks per year (IAEA research reactor database), would have used about 25 kg before conversion.

30. T. Dedik, I. Bolshinsky, and A. Krass, "Russian Research Reactor Fuel Return Program Starts Shipping Fuel to Russia," paper presented at 2003 International RERTR Meeting, Chicago, Illinois, USA, 5–10 October 2003 <http://www.rertr.anl.gov/RERTR25/PDF/Dedik.pdf>.

31. David Albright and Kimberly Kramer, "Civil HEU Watch: Tracking Inventories of Civil Highly Enriched Uranium," *ISIS*, February 2005, revised August 2005 <http://isis-online.org/global_stocks/end2003/civil_heu_watch2005.pdf>.

32. "Entering a New Era," *Nuclear Engineering International*, 8 January 2010 <http://www.neimagazine.com/story.asp?storyCode = 2055118>.

33. *China Today: Nuclear Industry, op. cit.* p. 239; The Magical Sword Literary and Art Society of Nuclear Industry, eds., *The Secret Course* (the second version) (Beijing: Atomic Energy Press, 1993), p. 301 (in Chinese).

34. *China Today, Nuclear Industry, op. cit.* pp. 305–306.

35. It is expected that China's first third-generation attack submarine (Type 095) will come into service around 2015, HansKristensen, "China'sNoisyNuclearSubmarines," <http://www.fas.org/blog/ssp/2009/11/subnoise.php>.

36. China reportedly has been building two (Type 094 *Jin*-class) ballistic-missile submarines since around 2003–2004. It is expected that about five such SSBNs will be built. HansKristensen, "TwoMoreChineseSSBNsSpotted," <http://www.fas.org/blog/ssp/2007/10/two_more_chinese_ssbns_spotted.php>.

37. See, e.g., Type 091 (*Han* Class) Nuclear-Powered Attack Submarine <http://www.sinodefence.com/navy/sub/type091han.asp>.

38. It is assumed the reactor operates with an average output of one-sixth of full power and the spent fuel has a uranium-235 burnup of 50 percent, and one kg of uranium-235 fission generates about 940 Megawatt-days of energy. Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review* 8, (Spring 2001); 95.

39. If a submarine was scheduled for launch before 1985, LEU may have had to be produced before 1980 to allow time for fuel fabrication, loading fuel into the reactor, and possible delays. The launch and initial operational capacity (IOC) of *Han*-class nuclear attack submarines are: Changzheng 1 (launched December 1970; IOC August 1974); Changzheng 2 (launched December 1977; IOC December 1980); Changzheng 3 (launched October 1983; IOC December 1984); Changzheng 4 (launched December 1985; IOC December 1987); Changzheng 5 (launched April 1990; IOC December 1990). Assuming the refueling interval is 10 years, then a total five cores were used for SSNs launched before 1985: Changzheng 1 (2 cores), Changzheng 2 (1 core), Changzheng 3

(1 core), Changzheng 4 (1 core), Changzheng 5 (0 core). "Type 091 (*Han* Class) Nuclear-Powered Attack Submarine," <http://www.sinodefence.com/navy/sub/type091han.asp>.

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

41. "China's Nuclear Tests: Dates, Yields, Types, Methods, and Comments," <http://www.nti.org/db/china/testlist.htm>.

42. This assumes 20 kg of HEU was used in each of the fission weapon tests. In the June 1967 3–3.3 MT thermonuclear weapon test, it is assumed that about 20 kT of the total yield came from the fission primary and about one-quarter of the yield in the thermonuclear secondary came from the fission of HEU, with about half of the HEU having fissioned. Frank von Hippel, Princeton University, personal communication, September 2010. This test would have consumed about 100 kg of HEU in the secondary. After plutonium became available in 1968, China may have shifted to using plutonium or composite uranium-plutonium pits since they allow the primaries to be more compact.

43. There were 18 tests after 1968 with yields above 20 kT that are assumed to have been thermonuclear weapon tests. The total yield of these 18 tests was about 19 MT.

44. In the U.S. 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 percent losses.

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

46. One contribution to the ± 25 percent uncertainty assumed for the estimated HEU production is due to the range of possible tails. For natural uranium feed producing 90 percent HEU, at a given separative work capacity, a tails assay of 0.5 percent would produce about 25 percent more HEU than a tails assay of 0.3 percent. There is no official information about tails assays in China's gaseous diffusion enrichment program.

47. This is significantly less than the 21.5 ± 4.5 tons of HEU estimated in Albright and Hinderstein, *op. cit.*

48. *China Today: Nuclear Industry, op. cit.*, p. 205.

49. *Ibid.* pp. 210–211.

50. W. Lewis and L. Xue, "Chinese Strategic Weapons and the Plutonium Option," *Critical Technologies Newsletter*, U.S. Department of Energy, Washington, D.C., April–May 1988, p. 12.

51. *China Today: Nuclear Industry, op. cit.,* p. 211.

52. *Ibid.,* p. 212.

53. *Ibid.,* p. 214. The reactor's power was increased by 10–15 percent through improvements in the cooling system. Fuel burn-up also was increased, and the number of full-power days went from the original design value of 288 days to 324 days per year.

54. See, e.g., Zhou Zhi, "Hegongyue 404 Jidi Chuangyue Huiyi," ("Recollections of the Pioneering Work of Plant 404"), in Chinese, 19 August 2007. The author was vice-minister of the former Ministry of Nuclear Industry, <http://qkzz.net/Announce/Announce.asp?BoardID=17100&ID=10015168>.

55. During the early 1980s, China planned to convert the reactor to the dual mission of producing electric power as well as plutonium. Work started in September 1984 and was planned to be completed in 1987, but the modification seems to remain unfinished. No electricity substation or transmission lines connected to the site have been seen on satellite images. *China Today: Nuclear Industry, op. cit.*, p. 91.

56. *China Today, Nuclear Industry, op. cit.,* p. 227.

57. For a burn up of 800 MWt-days/ton, each ton of spent fuel would contain about 0.7 kg weapon-grade plutonium. See, International Panel on Fissile Materials, "Appendix B, Production of Highly Enriched Uranium and Plutonium for Weapons," Global Fissile Material Report 2010, 2010 <http://www.fissilematerials.org/ipfm/site_down/gfmr10.pdf>.

58. *China's Nuclear Tests: Dates, Yields, Types, Methods, and Comments*, <http://www.nti.org/db/china/testlist.htm>.

59. Hui Zhang and Frank von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Gaseous-Diffusion Plants," *Science and Global Security* 8 (2000): 219. 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.

60. Operating at a capacity factor of 80 percent, a reactor of power 70–660 MWt could produce about 20–200 kg per year of weapon plutonium. This is a large range but it excludes a 1972 U.S. intelligence estimate that the Jiuquan reactor produced 300–400 kilograms of plutonium per year. U.S. Defense Intelligence Agency, *op. cit*.

61. International Panel on Fissile Materials, "Russia: Plutonium," Global Fissile Material Report 2010, *op. cit*., p. 46.

62. See, e.g., News from Chongqing Cable TV, 26 April 2010 (in Chinese); Peng Yining, "Nuclear Reaction to Tourist Attraction," *China Daily*, 22 June 2010 <http://www.chinadaily.com.cn/cndy/2010–06/22/content_10000111.htm>; and "Former Nuclear Plant Opening as Tourist Attraction," *China Daily*, 13 April 2010 <http://www.chinadaily.com.cn/china/2010–04/13/content_9719335.htm>.

63. The amount of plutonium produced per year by a reactor is estimated by: $R(\text{kg/yr}) = CPth\ (\text{MW})\alpha(\text{kg/MWd})365(\text{d/yr})$, where R is plutonium production rate (in kilograms per year); C is the capacity factor; *Pth* is the thermal power of the reactor (in megawatts); and α is the amount of plutonium produced per megawatt-day of operation.

64. It also assumes the amount of plutonium produced per MWt-day by the Jiuquan reactor is the same as for the U.S. Hanford graphite-moderated, water-cooled reactors (see International Panel on Fissile Materials, *op. cit*.). Between 1967–69, the reactor operated at an average burn-up of about 400 MWt-days/ton and produced 0.9 grams of plutonium per MWt-day. From 1970 until 1984, the reactor operated at an average burn-up of 800 MWd/t and produced 0.85 g/MWt-day.

65. Zheng Jingdong, retired senior engineer from Plant 821, blog, " Zai Qiangjian 821 Chang de Rizi Li," ("The Days of Racing to Complete the Plant 821") (in Chinese) 26 September 2009. <http://blog.163.com/zjd_8213701/blog/static/335820262009826631109 91>.

66. "The days of racing to complete the Plant 821," *op. cit.*; and "Liangwei Hedian Gongchen de Zhihui Rensheng, Jiangsu Gonggong Kejiwang Wendang: *Ren Wu*," ("The intelligent life of two heroes of nuclear power," document web of Jiangsu public science and technology: People) (in Chinese) 14 May 2007 <http://hi.baidu.com/lovechild/blog/item/f43d1a7a00a1eaec2e73b359.html>.

67. "The Intelligent Life of Two Heroes of Nuclear Power," *op. cit.*

68. The new enterprise was called the Sichuan Wuzhou Industry Company, a subsidiary of the China National Nuclear Company. The company declared bankruptcy in 2009 and the residents in the complex will move to new living areas <http://www.cnnc.com.cn/publish/portal0/tab283/info47848.htm>.

69. Norris et al., *op. cit.,* p. 350.

70. See, e.g., "The Days of Racing to Complete the Plant 821," *op. cit.*

71. It also assumes the amount of plutonium produced per MWt-day by the Guangyuan reactor is the same as for the U.S. Hanford graphite-moderated, water-cooled reactors (International Panel on Fissile Materials, *op. cit*.). For the whole operating period, the reactor is assumed to have operated at an average burn-up of 800 MWd/t and produced 0.85 g/MWt-day.

72. 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.

73. The uncertainty of ± 25 percent stems primarily from the uncertainty of the initial design powers of the two reactors.

74. Reported by Bill Gertz and Rowan Scarborough in "A Nation Inside the Ring," *The Washington Times*, 9 July 1999; and Norris and Arkin, *op. cit*.

75. See, e.g. Wright and Gronlund, *op. cit.* For the Jiuquan reactor, they assume a design power of 250 MWt that was later increased to 500 MWt. For the Guangyuan reactor, they assume a design power of 500 MWt that increased to 1000 MWt.

76. Communication received from China Concerning its Policies Regarding the Management of Plutonium, IAEA, INFCIRC/549/Add.7/8, 1 April 2008.

77. Deng Guoqing, China National Nuclear Corporation, "Overview of spent fuel management in China," International Conference on Management of Spent Fuel from Nuclear Power Reactors," Vienna, 31 May–4 June 2010 <http://www-ns.iaea.org/meetings/rw-summaries/vienna-2010-mngement-spent-fuel.htm>.