Estimating China's Production of Plutonium for Weapons

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This paper discusses the history of China's production of plutonium for nuclear weapons, and uses that history and analogies to the production process in the United States and Russia to estimate the amount of plutonium China produced at its two known facilities. That analysis leads to an estimate that China produced 2 to 5 tonnes of plutonium at these facilities before it ceased production around 1990. The paper describes how the analysis was done and what assumptions were used so that a reader can understand how the results are affected by different assumptions or by new information that might become available.

Given the lack of information available about most aspects of China's nuclear-weapon program, the estimate of plutonium production developed in this paper is necessarily rough. However, even a rough estimate is interesting since the size of China's fissile material stockpiles will influence China's willingness to join a multilateral "cut-off" convention to ban future production of fissile material for weapons or outside of safeguards.

History of Chinese Plutonium Production

Plutonium is produced by irradiating uranium-238 with neutrons in a nuclear reactor and then extracting the plutonium from the mixture of plutonium, uranium, and fission products that result from the fission of the uranium and plutonium. Thus a production complex must contain a production reactor and a reprocessing facility to separate the plutonium.

China is believed to have produced plutonium for weapons at two facilities: (1) the Jiuquan Atomic Energy Complex (also referred as Plant 404 or the Yumen or Subei facility, after a nearby city and county), where the first production reactor began operating in late 1966, and (2) the Guangyuan facility (or Plant 821), one of the so-called "Third Line" facilities, which probably began operating in the mid-1970s. Below we first describe the history of the facilities and then estimate their output. Our discussion of the Chinese production complex draws heavily on information available in the official Chinese history of its nuclear industry,[2] and on the work of Lewis and Xue.[3]

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[2]Li Jue, et al., eds., *Tang Tai Chung-kuo Ti Ho Kung Yeh* [China Today: Nuclear Industry] (First Edition) (Beijing, 1987). Selections are translated in Foreign Broadcast Information Service, US Department of Commerce Joint Publications Research Service, *JPRS Report—Science and Technology: China,* JPRS-CST-88-002, 15 January 1988 and JPRS-CST-88-008, 26 April 1988.

[3]John Lewis and Xue Litai, *China Builds the Bomb* (Stanford, CA: Stanford University Press, 1988) and John Lewis

The Jiuquan facility:

China received technical assistance in developing a plutonium production reactor from the Soviet Union in the late 1950s. Construction of the first reactor, which was a Soviet design, began in March 1960. In August of that year the Soviets withdrew technical assistance with construction barely underway and without providing much of the equipment and design drawings it had promised, which China was then forced to produce domestically.[4] The reactor is a light-water cooled, graphite moderated reactor that used natural uranium fuel.[5] The fuel elements originally used in the Chinese reactor are reported to have natural uranium cores with aluminum cladding, with a nickel coating between the uranium and aluminum for heat conduction.[6]

The Soviet production reactors that were built in the early 1950s at Chelyabinsk were similar to that of the early US production reactors at Hanford;[7] if this design was the basis of the Chinese reactor, then it is probably also similar to the Hanford reactors. However, the Chinese design might also have been based on the Soviet reactor that began operating in 1955 at Tomsk-7.[8]

The first chain reaction at the Jiuquan reactor was achieved in October 1966, and by the end of the year the reactor power reportedly reached 0.5% of the design maximum. *China Today* breaks the operating history of the reactor into three stages:[9]

> (1) 1967 through the first half of 1975, when scientists accumulated experience operating the reactor, improved the equipment, and reportedly achieved the reactor's design output;
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> (2) the second half of 1975 through 1980, when the productivity of the reactor reportedly exceeded the nominal design capacity;
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> (3) 1981 though the mid-1980s (when *China Today* was written), during which time the reactor was modified to produce civil power. (Dividing phases 2 and 3 at the year 1980

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and Xue Litai, "Chinese Strategic Weapons and the Plutonium Option," *Critical Technologies Newsletter*, US Department of Energy, Office of Classification and Technology Policy (DOE/OTP/CTN-88-004/005), April/May 1988, pp. 4-14.

[4]*China Today*, p. 204; Lewis and Xue, “Chinese Strategic Weapons,” pp. 6-7 and *China Builds the Bomb* p. 112. Lewis and Xue note that none of the vital equipment had been delivered, such as fuel rods, main pumps, and heat exchangers, although the Soviets had supplied "preliminary designs" for the fuel rods, fuel channels, and other parts of the reactor core.

[5]*China Today*, p. 203.

[6]*China Today*, p. 193.

[7]David Holloway, *Stalin and the Bomb* (New Haven: Yale University Press, 1994), p. 183 and Thomas B. Cochran, Robert S. Norris, and Oleg A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin* (Boulder, CO: Westview Press, 1995), p. 73. For information on the Hanford reactors, see Thomas B. Cochran, William M. Arkin, Robert S. Norris, and Milton M. Hoenig, *Nuclear Weapons Databook, Volume II: US Nuclear Warhead Production* (Cambridge, MA: Ballinger, 1987), pp. 58-66.

[8] Oleg Bukharin, Princeton University, personal communication, December 2002.

[9]Except where noted, the material in this section is taken from *China Today*, pp. 210-215.

appears only to correspond to a division between China's five-year planning periods.)

Stage 1 was characterized by frequent failures of various subsystems. Initially, repairing the reactor required that it be shut down, but after 1970 fewer shutdowns were reportedly necessary, thus increasing the fraction of time the reactor was operating.[10] Major repairs and maintenance reportedly shut the reactor down for most of 1974, but by the first half of 1975 the reactor is said to have reached its design capacity for the first time. Operation of the facility was also reportedly interrupted during the late 1960s and early 1970s by the turmoil of the Cultural Revolution.[11]

During stage 2, *China Today* states that the reactor had a good operating record and exceeded the design capacity. Other sources, however, suggest that problems continued to plague the reactor.[12]

Safety tests run in 1975 reportedly showed that the reactor could be run at higher than design power, and the following year a program was begun to address two major limitations of the reactor design: limited cooling capacity and what *China Today* calls "low core reactivity." It is worth noting that the power at which both the early US and Russian production reactors operated was increased considerably--by factors of two to nine--over their lifetimes. These higher operating powers were possible in large part because of improvements in the cooling system, which could carry away the increased heat generated in the core when operating at these higher powers.[13] The description of the changes made to the cooling system of the Jiuquan reactor suggests similar steps were taken and that the capacity of the cooling system was increased considerably during this time by installing better pumps and more effective heat exchangers. It also appears that the original cooling towers were sufficient to accommodate these changes, suggesting that they were over-designed for the original operating power.

The power of the reactor could also have been increased by adding some slightly enriched uranium to the fuel. Such fuel was used in the US N-reactor at Hanford.[14] We do not know whether such fuel was used by China, but that may be what *China Today* means by increasing the core reactivity.[15] On the other hand, increasing reactivity may simply refer to taking steps to

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[10]A key parameter that describes the operation of a reactor is the "capacity factor," which is the total energy the reactor produced in a given time divided by the maximum energy it could have produced if it had run continually and at maximum power.
[11]Lewis and Xue, "Chinese Strategic Weapons," pp. 12-13.
[12]David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (New York: Oxford University Press, 1997), p. 76.
[13]The US Department of Energy Report *Plutonium: The First 50 Years* (DOE/DP-0137), February 1996, p. 30 states that similar power increases at the Savannah River reactors resulted from "engineering enhancements such as installing larger pumps, more heat exchangers, larger pipes and optimizing the reactor physics, internal coolant flow designs, and improved fuel element designs."
[14]Cochran, *et al., US Nuclear Warhead Production*, p. 66. One can also add a ring of fuel rods containing highly enriched uranium around the outside of the core to increase the neutron flux in this region and thus flatten the flux profile in the core (Tom Cochran, personal communication, 28 August 1995.
[15] China first produced highly enriched uranium (HEU) in 1964 (Albright, *et al., Plutonium and Highly Enriched Uranium 1996*, p. 126). It is not known whether it used some of its enrichment capability to produce fuel for its plutonium production reactors, in addition to producing HEU for weapons.

reduce neutron losses. *China Today* states that as of 1979, continuing modifications of the reactor were leading to a steady increase in production.

Also during stage 2, the specific burnup of the fuel was reportedly increased, meaning that the fuel was irradiated for a longer period of time in the reactor.[16] Increasing the specific burnup reduces the amount of fuel used by the reactor to produce a given amount of plutonium, and therefore reduces both the amount of spent fuel that must be reprocessed and the amount of time the reactor is down for refueling. However, increasing the specific burnup increases the fraction of Pu-240 in the plutonium that is produced. Pu-240 emits neutrons spontaneously, and using plutonium with a high concentration of Pu-240 in a nuclear weapon can cause the fission reaction to begin too rapidly in a Nagasaki-type (solid-core) design, so that the plutonium is never compressed to optimum density. This "pre-detonation" can cause the yield of the weapon to be lower than the design value.[17] So-called "weapon-grade" plutonium contains 6% or less Pu-240 (corresponding to a specific burnup of less than about 700 MWd/t) while "super-grade" plutonium contains less than 2-3% Pu-240 (corresponding to a specific burnup of 200-300 MWd/t) (see Appendix A).

The United States initially operated its plutonium production reactors at low burnup; estimates suggest that the first atomic bomb the United States exploded at the Trinity test used plutonium containing only a percent or two of Pu-240.[18] However, most current US weapons are believed to use plutonium with 5-6% Pu-240 (corresponding to burnups of 550-670 MWd/t).[19] Like the United States, China may have originally operated its reactors with low burnup to produce super-grade plutonium, but it is likely that China also increased its burnup and began to use weapon grade plutonium.

Because poor design of the fuel elements can cause them to swell and buckle unless they are used at low burnups, this also suggests that China initially operated at low burnups.[20] Lewis and Xue state that the increased cooling prolonged the life of the fuel elements, which could also have allowed China to increase the specific burnup.[21]

China Today states that as a result of efforts to increase the operating time of the reactor, the

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[16] The "specific burnup" of the reactor fuel is a measure of the fraction of the fuel that has been burned, often reported in terms of thermal energy produced by fission per initial mass of fuel. The unit used here is megawatt-days per metric tonne of fuel (MWd/t).

[17] J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security* **4**, 1993, p. 111-128; Egbert Kankeleit, Christian Küppers, and Ulrich Imkeller, "Report on the Usability of Reactor Plutonium in Weapons" (in German), Institute fur Kernphysik, Technische Hochschule Darmstadt, December 1989.

[18] Tom Cochran, personal communication, 15 January 1996. See also Mark, "Explosive properties."

[19] Nuclear weapons can be made with plutonium containing higher levels of Pu-240, but the increased level of radiation can create health hazards and somewhat complicates the bomb design. Warheads on US submarine-based missiles are believed to use plutonium with very low Pu-240 content so that there is less radiation danger to the submarine crew (Marvin Miller, personal communication, 28 August 1995).

[20] The original Soviet production reactor at Cheliabinsk (the A reactor) had these problems. See Holloway, *Stalin and the Bomb*, p. 187 and Cochran et al., *Making the Soviet Bomb*, p.77.

[21] Lewis and Xue, "Chinese Strategic Weapons," p. 9.

reactor reached a peak of operating 244 days per year, which is said to exceed the design value by 36 days. (It is not clear whether the "design value" refers to the design before or after the modifications to the reactor.) If the reactor operated at full power during the 5 ½ years of stage 2, these figures would correspond to a design capacity factor of 0.57 and a peak of 0.67. Lewis and Xue cite higher numbers: they state that the modifications of the reactor increased the number of operating days per year from under 290 to 324.[22] We note that Cochran et al. assumed a capacity factor of 0.7-0.8 in estimating the plutonium produced by the original US reactors at Hanford.[23]

In 1981, China reportedly began feasibility studies for converting the reactor to produce both plutonium and electricity, and modifications to the reactor began in 1983. These modifications would have caused the reactor to be shut down for some period, but there is no reason to believe that co-generation would have reduced the plutonium production once the reactor was back online. Modifications to increase the reactor power may also have continued; although no such modifications are explicitly discussed in *China Today*, it does state that co-generation would require "improved hydrolic parameters in the loops," which may suggest continued improvements in cooling capacity that could result in higher operating power.

Plutonium production at the Jiuquan site is reported to have stopped in 1984.[24] It is possible that the reactors continued to operate to produce electricity after the demand for plutonium ended, as has happened in Russia. Chinese studies are said to show that the Jiuquan reactor should have a 30-year lifetime, which would mean that it should have been shut down in 1995 or 1996.[25]

Reprocessing at the Jiuquan facility:

China first reprocessed its irradiated fuel at an "intermediate pilot plant" that began operating in September 1968 and was shut down in the early 1970s.[26] The plant had two parallel production lines and a reported design capacity of 400 kg of spent fuel per day. Lewis and Xue state that the plant "on average, operated one or both lines continuously 250 days per year."[27] If the design capacity were reached and both lines operated 250 days per year, these numbers indicate the plant

[22] Lewis and Xue, "Chinese Strategic Weapons," p. 9.
[23] See Cochran, *et al., US Nuclear Warhead Production,* p. 64, Caption to Table 3.3 and Cochran *et al., Making the Russian Bomb,* p. 277.
[24]Mark Hibbs, "China Said to be Preparing for Decommissioning Defense Plants," *Nuclear Fuel*, 17 May 1999, p. 11. Dr. Zhang Hui, in his paper "A Discussion of China's Nuclear Transparency Options," *Proceedings of the 42nd Annual Meeting of the Institute for Nuclear Materials Management*, Northbrook, IL, 2001 appears to state that production at both of China's plutonium production facilities ended around 1991. However, he has clarified that his understanding is that all Chinese plutonium production ceased by around 1991, but that production at the Jiuquan facility had stopped earlier than that (personal communication, October 2002).
[25] The lifetime of a reactor depends upon many things. For a graphite-moderated reactor, the radiation-induced swelling of the graphite can be one of the key issues.
[26]*China Today*, p. 216. Hibbs, "China Said to be Preparing" states that the Jiuquan plant used a Soviet separation process based on precipitation of sodium uranyl acetate. *China Today*, however, states that the Chinese program began in 1956 intending to use the Soviet method, but in 1964 instead decided to use the Purex method.
[27] Lewis and Xue, "Chinese Strategic Weapons," p. 11.

could therefore process a maximum of 100 tonnes of spent fuel per year, which would result in about 50 kg per year of plutonium with 6% Pu-240, or less than 30 kg per year at 3% Pu-240. Since this maximum capacity assumes that both lines were operating 250 days per year, the actual output of the plant was probably lower than these figures; Appendix B shows that the total annual capacity was likely closer to 60 tonnes. Moreover, *China Today* states that plutonium production was actually slightly lower than the design value. After the main reprocessing plant began operating in 1970, the pilot plant was said to be used for purposes other than extracting weapon-grade plutonium, but it is unclear whether all such extraction stopped. The plutonium used in the first Chinese plutonium bomb test on December 27, 1968 is said to have come from the pilot plant.[28]

Construction of the main reprocessing plant began in parallel with the pilot plant, and as a result not all of the lessons learned in the pilot plant could be incorporated. The main plant began operating in April 1970, but operation was unreliable and output was low. These problems were reportedly solved by the beginning of 1972.[29] Subsequent improvements to the plant were said to increase its capacity by 40-50% over its design capacity. Thus, it may be reasonable to assume this facility could process several hundred tonnes of spent fuel annually (as we discuss below).

The Guangyuan facility

In the 1960s and early 1970s, China began to build a number of military facilities at remote locations that were intended to be less susceptible to attack than the original nuclear weapon-related facilities. These are referred to as the "Third Line" facilities. A second plutonium production facility, known as the Guangyuan facility, is reported to have been built in Sichuan. Little is known about the plant, but it is believed to contain China's largest production reactor and a chemical separation plant.[30] Lewis and Xue refer to this production reactor as “a very large reactor.”[31] Plutonium production for weapons at this facility apparently began in the mid-1970s and is believed to have stopped in the late 1980s or early 1990s.[32]

Estimating China's Military Plutonium Production

The range of published estimates of China's military plutonium production is very broad. In their first book estimating fissile material stockpiles, Albright, Berkhout, and Walker[33] estimated that

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[28] Lewis and Xue, “Chinese Strategic Weapons,” p. 9.
[29] *China Today*, p. 232.
[30] Albright, Berkhout, and Walker, *Plutonium and Highly Enriched Uranium 1996*, p. 76 and Robert S. Norris, Andrew S. Burrows, and Richard W. Fieldhouse, *Nuclear Weapons Databook, Volume V: British, French, and Chinese Nuclear Weapons* (Boulder, CO: Westview Press, 1994), p. 350.
[31] Lewis and Xue, “Chinese Strategic Weapons,” p. 14.
[32] Hibbs, “China Said to be Preparing” states that plutonium production stopped “at the end of the 1980s.” Norris, Burrows, and Fieldhouse, *British, French, and Chinese Nuclear Weapons*, p. 350 state that production stopped in 1991.
[33] David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992* (New York: Oxford University Press, 1993), p. 46. The second edition of their book uses the

China had produced from 1 to 4 tonnes of plutonium. On the other hand, Norris, Burrows, and Fieldhouse[34] give an estimate of roughly 4 to 7 tonnes with an upper bound of 15 tonnes. The difference in these estimates appears to result primarily from estimates of the power of the production reactors, as we discuss below. We attempt in this section to develop an independent estimate.

The amount of plutonium produced in a reactor depends both on the power and the operating history of the reactor. The amount of plutonium that could be produced annually by a reactor operating at a constant power and capacity factor can be estimated by:

$$X_{Pu}\left(\frac{kg}{yr}\right) = C\ P_{th}(MW)\ \beta\left(\frac{kg}{MWd}\right) 365\left(\frac{d}{yr}\right) \qquad Eq.1$$

where X_{Pu} is the amount of plutonium produced annually (in kilograms per year); C is the capacity factor, which is typically between 0.5 and 1; P_{th} is the thermal power of the reactor (in megawatts); and β is the amount of plutonium produced per megawatt-day of operation, which depends on the specific burnup of the fuel and thus on the fraction of Pu-240 in the extracted plutonium. For burnups that give a Pu-240 content in the range of 3-6%, the value of β is in the range 9.0-8.5 x 10^{-4} kg/MWd, or just under 1 gram per megawatt-day (see Appendix A; the value of β for US plutonium production at Hanford was[35] 8.2 x 10^{-4} kg/MWd).

The reactor power, the capacity factor, and the specific burnup of the fuel will, in general, change over the lifetime of the reactor. We estimate these quantities based in part on the history of the Jiuquan reactor sketched above, as well as on knowledge of the US and Soviet production programs.

Estimating the Reactor Power at Jiuquan:

There is little reliable information about the power of either of China's production reactors. For the Jiuquan reactor, Albright *et al.*,[36] assume a reactor in the range of 400-600 MWth. Norris *et al.*,[37] on the other hand, state that the reactor may have been able to produce 300-400 kg of plutonium annually, which would require a maximum power of 1400-1900 MWth, assuming a capacity factor of 70% and 6% Pu-240 content. This figure appears to be based on a US Defense Intelligence Agency (DIA) estimate from 1972, which likely came from satellite photos of the facility.

Several other references also give estimates of reactor size or annual plutonium production, but

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estimates derived in an earlier version of this paper.

[34]Norris, Burrows, and Fieldhouse, *British, French, and Chinese Nuclear Weapons,* pp. 11 and 350.

[35] Tom Cochran, personal communication, January 1996.

[36]Albright, Berkhout, and Walker, *World Inventory 1992*, p. 46.

[37]Norris, Burrows, and Fieldhouse, *British, French, and Chinese Nuclear Weapons,* pp. 11 and 350.

the reliability of these figures is uncertain. A 1969 *Sunday Times of London* article, written by a journalist who visited China, states that a Chinese source told him that the Jiuquan facility could produce more than 300 kg of plutonium annually.[38] A 1985 article in *The China Business Review* states without giving a source that this plant could produce about 400 kg annually.[39]

On the other hand, a German study gives a lower figure, stating that the Jiuquan reactor power is 600 MWth and produces 200 kg weapon-grade plutonium per year. [40] We note that a 600 MWth reactor could only produce 200 kg of plutonium annually if it operated with a capacity factor of 100%. Assuming a capacity factor of 70% and 6% Pu-240, a 600 MWth reactor could produce only 130 kg of plutonium annually; alternately, producing 200 kg annually would require a 900 MWth reactor.

As a base case, we estimate that the initial design power of the reactor was roughly 250 MWth and that later improvements may have roughly doubled the power. As we discuss below, this estimate is based on three factors: (1) the US and Soviet experience with their early plutonium production reactors, (2) the size of the Jiuquan reactor's cooling towers, and (3) the reprocessing capacity at Jiuquan.

US and Soviet experience with their early plutonium production reactors

The original US plutonium production reactors at Hanford, which were built in the mid- to late-1940s, began operating with a power of 250 MWth. The output of these reactors was upgraded to 1440 MWth by the late 1950s and eventually to over 2000 MWth.[41] As noted above, the Chinese reactor may have been based on a Soviet design believed to be similar to the Hanford reactors. These Soviet production reactors, which came online in the early 1950's at Chelyabinsk, had an initial power of 300 MWth, and were eventually increased to 1200 MWth. As noted above, the Chinese reactor may instead have been based on the design of the Soviet production reactor at Tomsk-7, which came online in late 1955 with a power of 600 MWth, and increased over time to 1200 MWth.[42]

Like the US and Russian reactors, the power of the Chinese reactor likely increased over time, possibly by a significant amount.

Jiuquan cooling towers.

It appears possible to put an upper limit on the reactor power by analyzing a photograph of the cooling towers of the Jiuquan reactor (Figure 1) and a satellite photo of the towers (Figure 2).

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[38]Francis James, "Mao's wild, wild west: China's nuclear Zone--first on the inside," *Sunday Times of London*, reprinted in *Atlas*, August 1969, pp. 19-23.

[39]Bradley Hahn, "China's Nuclear History," *The China Business Review*, July-August 1985, pp. 28-31.

[40] H.-M. Göbbel, *VR China: Atomwirtschaft und politik* (München: Trikont-Verlag, 1980).

[41] T. Cochran et al., *Nuclear Weapons Databook Volume II*, p. 59-61.

[42]Anatoli Diakov, "Disposition of Weapon's-Grade Plutonium in Russia: Evaluation of Different Options," in Proceedings of the NATO conference "Dismantlement and Destruction of Chemical, Nuclear, and Conventional Weapons" (Kluwer Publisher, 1996); Diakov, personal communication, January 1999 Bukharin, personal communication December 2002.

Two analyses suggest that each of the six towers could cool a maximum of 100-200 MWth of reactor power, depending on the design of the cooling system.[43] It is common to reserve roughly one-third of the towers as spares, so that a couple of the towers may not be used under normal conditions. Assuming that four of the towers were normally operated suggests that the cooling was adequate for a 400-800 MWth reactor.[44] It should be kept in mind, however, that especially for an early design the cooling capacity of the reactor may have been overdesigned so that the actual power of the reactor may have been smaller, perhaps considerably so, than the maximum suggested by the cooling capacity.

Figure 1. The cooling towers for the Jiuquan reactor.
(From *China Today*, Figure 49.)

[43] One estimate of the cooling capacity was provided as a personal communication from a US Department of Energy source (1995), and gave a range of 100-200 MWth. A second estimate was made by Dr. Zhang Hui, who estimated a maximum cooling capacity per tower of roughly 140 MWth (personal communication, 1998).
[44] Zhang Hui estimates that if other heat losses are included, four towers could cool a maximum of roughly 650 MWth. He has also estimated the maximum power in a second way. By comparing the size of the cooling towers to those of the Soviet Tomsk-7 reactor, which is believed to be similar to the Jiuquan reactor, he estimates that the power of the Jiuguan reactor is less than 600 MWth (Zhang Hui, personal communication, 2002).

Figure 2. Satellite photograph of the Jiuquan facility. The cooling towers are clearly visible in the lower left corner. A perimeter fence is apparent as the rectangular line surrounding the complex. The reactor is believed to be the dark square just right of center in the photograph, which appears to have a tall exhaust stack attached to it. (Declassified U.S. Corona Satellite Image, Corona Mission 1117 on 30 May 1972, KH-4B system,1.8 m spatial resolution.)

The cooling capacity of the towers does, however, place an upper bound on the power of the reactor. If the analysis of the towers is correct, it rules out a reactor in the 1000-2000 MWth range, and thus would rule out the high estimates of annual plutonium production, at least at the Jiuquan facility.

Based on these considerations, our base case assumes that after reaching its original design power in 1975 (as reported in *China Today*), the power level of the Jiuquan reactor was roughly doubled by the end of 1982, when the reactor was shut down to be modified to produce electricity as well as plutonium. A power level of roughly 500 MWth appears to be consistent with an estimate of the cooling capacity of the cooling towers, and with the time over which the early US production reactors doubled their power. China may have made further efforts to increase the power level of the reactor after 1983, but *China Today* refers only to modifications to allow it to generate electricity. For our base case we therefore assume the power level remained roughly constant after 1983.

Reprocessing capacity at Jiuquan

The reprocessing capacity at Jiuquan may also provide information about the reactor power. The intermediate pilot plant for reprocessing at Jiuquan was built to proof-test a Purex-type method while a larger plant was being built. As noted above, the pilot plant is reported to have had two parallel production lines and could process up to 400 kg of spent fuel daily, meaning that each line could process up to 200 kg per day. On average, one or both lines are said to have operated over 250 days a year.[45] This statement implies that both lines did not operate the full 250 days, so that the capacity of the pilot plant was in the range 50-100 tonnes per year, assuming they were used at full capacity when they were operating, and was likely in the low end of that range (see Appendix B).

The spent fuel from a reactor of the Jiuquan type could not be stored for more than several months because of corrosion and would have to be reprocessed during that time. Using this fact, the capacity of the pilot plant can be used place a limit on the reactor's initial power.[46] The total amount of spent fuel *T* (in tonnes) produced by a reactor in a year is given by:

$$T(t) = C\ P(MW)\ \frac{1}{B}\left(\frac{t}{MWd}\right)365\left(\frac{d}{yr}\right) \qquad Eq.2$$

where *C* is the average capacity factor, *P* is the average operating power (in MWth) of the reactor, and *B* is the specific burnup of the fuel. Assuming a capacity factor of 0.4 during the early operation of the reactor, and requiring that *T* be less than about 60 tonnes per year so that it would not exceed the capacity of the reprocessing plant, Eq. 2 implies that the reactor power must have been less than about 280 MWth if it was producing weapon-grade plutonium, or less than about 100 MWth if it was producing super-grade plutonium. As noted above, we assume that China began producing weapon-grade plutonium early on. The bound on the power increases if the capacity of the reprocessing plant was greater or the initial capacity factor was lower.

China's current program for reprocessing civil nuclear fuel includes a pilot plant with a similar capacity (50 tonnes of heavy metal per year, which was scheduled to begin operating in 2000) to be followed by a commercial-scale plant with a capacity of 400 to 800 tonnes per year.[47] If a similar scaling occurred in the military case, the capacity of the large-scale military reprocessing plant might also be in the range of 400 to 800 tonnes of spent fuel per year; the actual capacity of this plant, of course, might be greater than this.

To estimate the amount of spent fuel produced by the production reactor, we assume that the

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[45]Lewis and Xue, p. 11.
[46] This argument is due to Oleg Bukharin, Princeton University, personal communication, December 2002).
[47]Zhang Hui, "Economic Aspects of Civilian Reprocessing in China," in *Proceedings of the 42nd Annual Meeting of the Institute for Nuclear Materials Management*, Indian Wells, California, July 15—19, 2001, and Sun Donghui, "Backend of Nuclear Fuel Cycle in China," presentation at the 28th Japan Atomic Industrial Forum (JAIF) Annual Conference, April 1995.

reactor could produce weapon-grade plutonium (with 6% Pu-240 and specific burnup of 600-700 MWd/t) with a capacity factor of 65-70% and super-grade plutonium (with 3% Pu-240 and specific burnup of 300 MWd/t) with a capacity factor of 55-60%.[48] Using these assumptions, a 500 MWth reactor would produce 200-350 tonnes of spent fuel per year, and a 1500 MWth reactor would produce 600-1050 tonnes of spent fuel per year, where the lower figure corresponds to the production of weapon-grade plutonium and the higher figure to super-grade.

We assume the main reprocessing plant was designed to have a capacity more than sufficient to reprocess the projected amount of spent fuel from the reactor. If the plant was built assuming a significant amount of super-grade plutonium would be reprocessed, then these estimates would appear to rule out a reactor as large as 1500 MWth. However, if most of the material to be reprocessed was weapon-grade plutonium, then a better estimate of the capability of the reprocessing plant is required to give a useful bound on the reactor power.

Viewed in the opposite way, however, the limit discussed above for the power of the reactor based on the cooling towers suggests that the reprocessing plant with a capacity of 400 tonnes per year would have been sufficient, and suggests the plant was designed with a capacity at the low end of range cited above.

Estimating Production at the Jiuquan Facility:

As a base case, we break the time the Jiuquan reactor was operating into three phases. We model the power of the reactor as (1) increasing linearly from zero to 250 MWth from the end of 1966 to mid-1975, (2) continuing to increase linearly to 500 MWth from mid-1975 through 1982, and (3) remaining constant at 500 MWth from 1983 through the end of production in 1984.

Based on the description in *China Today* we assume that the specific burnup of the fuel was originally low (we use 300 MWd/t), but that it increased to 600 MWd/t early in phase 2. We further assume the reactor was closed for repairs during 1974 and did not operate,[49] and that it did not operate during 1983 when it was being modified to generate electricity.

The peak annual capacity factor of the reactor during phase 2 was said to be 67%, with a design value of 57%. The early phase of operation was said to be plagued by frequent shutdowns, which would reduce the capacity factor. Moreover, a smaller specific burnup of the fuel in the early phase of operation would lead to a lower capacity factor than in later phases if the reactor needed to be shut down for refueling. For the base case we assume an average capacity factor of 40% during the first phase of operation, a value of 60% during the second phase, and a value of 65% during the final stage. Because we assume the reactor power was very low during the initial period, the estimate of plutonium production is relatively insensitive to the value of the capacity factor during this period.

[48] Decreasing the burnup increases the amount of time the reactor must be down for refueling.
[49] *China Today*, p. 211.

Assuming the power levels change linearly during these three phases of operation, Eq. 1 can be used to derive the following expression for the total plutonium production during these three phases:

$$X_{Pu}^{tot}(kg) = \frac{365}{2}\left(C_1\beta_1 Y_1 P_1 + C_2\beta_2 Y_2 (P_1 + P_2) + C_3\beta_3 Y_3 (P_2 + P_3)\right) \qquad Eq.\,3$$

where for phase number i, C_i is the average capacity factor, β_i is the kilograms of plutonium produced per megawatt-day of operation, Y_i is the number of years during the period that the reactor was operated, and P_i is the operating power level (in MWth) of the reactor at the end of the period.

Thus our base case uses the following values:

$Y_1 = Y_2 = 7.5$ years; $Y_3 = 1$ year
$\beta_1 = 0.90$e-3 kg/MWd; $\beta_2 = \beta_3 = 0.85$e-3 kg/MWd
$C_1 = 0.4$; $C_2 = 0.6$; $C_3 = 0.65$
$P_1 = 250$ MWth; $P_2 = P_3 = 500$ MWth

These values lead to an estimate of 0.75 tonnes of plutonium produced over the lifetime of the Jiuquan facility.

To illustrate how sensitive this estimate of plutonium production is to variations in the values of various parameters, we consider the following excursions around the base case.

Assuming that the reactor power was lower by 20%, with $P_1 = 200$ MWth and $P_2 = P_3 = 400$ MWth, all else being equal, the plutonium production would drop to 0.60 tonnes. If instead it was higher by 20%, with $P_1 = 300$ and $P_2 = P_3 = 600$, the production would increase to 0.90 tonnes.

Recall from the discussion of the capacity of the cooling towers that we estimate an upper bound of the power of the reactor in the range of 400 to 800 MWth. If the reactor power increased steadily from 250 to 800 MWth ($P_1 = 250$, $P_2 = 500$, $P_3 = 800$, $Y_1 = 7.5$, $Y_2 = 5$, $Y_3 = 3.5$), the plutonium production would have been 0.93 tonnes. If the original power was 400 and it increased to 800 ($P_1 = 400$, $P_2 = 800$, $P_3 = 800$), the total production would be 1.2 tonnes.

Using the power estimates of the base case, a capacity factor of 0.3 during the initial phase would reduce the estimate by 30 kg. Reducing the capacity factor during both the second and third phase by 0.1 ($C_1 = 0.4$, $C_2 = 0.5$, $C_3 = 0.55$) would reduce the total production by roughly 0.1 tonnes, while raising them both by 0.1 would increase total production by the same amount.

If the second phase was a year longer than assumed in the base case, the total production would increase to 0.82 tonnes; if instead the third phase was 2 years rather than 1, production would increase to 0.85 tonnes.

Based on these figures, and assuming the basic assumptions underlying our base case are roughly correct, we estimate the production at Jiuquan is in the range of 0.5 to 1.5 tonnes. However, if our analysis of the reactor power is significantly wrong, or if the operation of the reactors remained poor after 1975 as some sources suggest, the production figure could fall outside this range.

Estimating Production at the Guangyuan Facility:

Little is known about the Guangyuan facility. It is important to note that the reactor is believed to have begun operating in the mid-1970s, and was thus being built concurrent with phase 1 of operation of the Jiuquan reactor—before the Jiuquan reactor had reached its full design power. Thus it is unclear to what extent the Guangyuan design benefited from experience with the Jiuquan reactor. Moreover, while most reports suggest this reactor is much bigger than that at Jiuquan, is it not clear to what extent China would have attempted to scale up the Jiuquan design and build a much larger reactor before it had experience with the first reactor. The operating experience from the Jiuquan reactor, however, may have allowed the second reactor to come online more quickly and decreased its down time.

Thus, a reasonable model of this reactor may be that it was moderately larger than the Jiuquan reactor, but that it was able to reach the design power more quickly and that efforts to increase its power were conducted roughly in parallel with the efforts at Jiuquan. Moreover, it probably would have been operated at high specific burnup for most or all of its lifetime. We stress, however, that the uncertainty about the reactor power leads to a significant uncertainty in the plutonium production at this reactor.

Based on this model, our base case assumes that this reactor began operating in 1975 with a design power of 500 MWth, which was achieved after a year of operation, and that the power increased from 500 to 1000 MWth during the next seven years of operation. We then assume it operated at this power for another 7 years at somewhat higher capacity, until it was shut down around 1990. Our base case uses the following values:

Y_1 = 1 year; Y_2 = 7 years; Y_3 = 7 years
$\beta_1 = \beta_2 = \beta_3$ = 0.85e-3 kg/MWd
C_1 = 0.5; C_2 = 0.6; C_3 = 0.7
P_1 = 500 MWth; $P_2 = P_3$ = 1000 MWth

These estimates give a plutonium production of 2.5 tonnes.

As above, we again calculate some variations around the base case. If the initial power of the reactor was 400 MWth and it increased to 800 MWth by the end of phase 2 and then stayed constant, production would have been 2.0 tonnes. If the power increased more slowly than assumed in the base case, so that P_2 = 750 MWth and P_3 = 1000 MWth, production would decrease to 2.2 tonnes from the base case. If instead, the power increased to 1500 MWth by the end of the third phase, then production would be 2.9 tonnes.

If, returning to the base case, it took two years to reach the design power, so that $Y_1 = 2$, $Y_2 = 7$, $Y_3 = 6$, then production would be reduced by 0.1 tonne. If it operated with the base-case parameters but the third phase was a year longer, production would have increased by 0.2 tonnes.

Changing the capacity factors in either phase 2 or 3 by 0.1 would change the plutonium production by 0.2 to 0.3 tonnes.

Based on these variations, we estimate a range of 1.5 to 3.5 tonnes for the production of the Guangyuan facility.

Thus, we estimate that the total plutonium production at the two plants is roughly 2-5 tonnes.

It is important to keep in mind that since there is little hard evidence available on the production facilities, and in particular on the power and operating histories of the reactors, these values are suggestive at best. For example, there are rumors that one of the production facilities had a fire during the 1970s that seriously crippled the plant. If true, such an occurrence would reduce the total estimate, possibly by a significant amount. Moreover, it appears that a large portion of China's plutonium may have been produced at the Guangyuan factility, about which very little is publicly known. As noted above, it is possible that the reactor power is larger, perhaps significantly, than assumed here.

However, as more information becomes known about the facilities, this methodology can be used to produce refined estimates. One source of information that could be useful in placing a limit on the power of the Guangyuan reactor would be obtaining a satellite photo of the facility in order to analyze the cooling towers.

A more detailed estimate of plutonium production at these facilities would also have to take into account tritium production, since using the reactors to produce tritium would reduce the amount of plutonium they could produce.

Conclusion

In their book on fissile material stocks, Albright, Berkout, and Walker estimate that the total amount of plutonium contained in Chinese nuclear weapons is 1 to 2 tonnes.[50] This estimate is uncertain because little is known about either the size of the Chinese arsenal or the amount of plutonium used in individual Chinese weapons.

Our estimate of a total production of 2 to 5 tonnes of plutonium suggests that the stockpile of

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[50] Albright, Berkout, and Walker, *Plutonium and Highly Enriched Uranium 1996*, p. 77.

plutonium not in weapons is probably 4 tonnes or less, and possibly much less.[51]

The size of China's plutonium stocks could have implications for future expansion of its nuclear arsenal, either as part of its modernization plans or in response to a US deployment of a ballistic missile defense system. For example, if China were to increase the number of warheads on long-range missiles from the current level of roughly 20 to a level of 75 to 100, as suggested by the December 2001 US National Intelligence Estimate (NIE),[52] that could require 0.2 to 0.4 tonnes of plutonium, assuming these warheads contained 3 to 5 kilograms of plutonium each. A buildup to 200 warheads on long-range missiles—a number reportedly suggested by the 2000 NIE[53]—would require 0.6 to 0.9 tonnes of plutonium.

Thus, unless China dismantled some existing warheads on shorter range systems and reused the plutonium, limits on its plutonium stocks might place a bound on how much it could expand its long-range arsenal without restarting plutonium production. This may be an important consideration to China if it wants to keep open the option of expanding its strategic nuclear forces in response to possible US missile defense deployments. Indeed, while Chinese officials stated in the mid-1990s that China was no longer producing fissile material for weapons and had no plans to resume, China has resisted efforts to negotiate a formalized fissile material cutoff treaty.[54]

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Appendix A: Specific burnups and plutonium production

The table below gives the percent concentration of plutonium isotopes in the plutonium produced by the Hanford B reactor as a function of fuel burnup (data provided by Tom Cochran) and the amount of plutonium produced per metric ton of spent fuel (data from Dick Libby, "Nuclear Fuel Cycle and Nuclear Reactors" (unpublished)). Burnup is given in units of megawatt-days of reactor operation per metric ton of spent fuel.

The value of β, which gives the mass of plutonium produced per megawatt-day of operation, is

[51] If the service life of Chinese warheads is short, so that they are remanufactured relatively frequently, China might have substantial amounts of plutonium in the production pipeline, which would reduce the amount available for expanding its arsenal (Oleg Bukharin, Princeton University, personal communication, December 2002).
[52] National Intelligence Council, "Foreign Missile Developments and the Ballistic Missile Threat Through 2015 (December 2001), (available at http://www.cia.gov/nic/pubs/other_products/Unclassifiedballisticmissilefinal.htm)
[53] Steven Lee Myers, "U.S. Missile Plan Could Reportedly Provoke China," *New York Times*, 10 August 2000.
[54] See, for example, Rebecca Johnson, "CD Closes 2002 Still Deadlocked," *Disarmament Diplomacy*, October-November 2002.

found by dividing the number in the sixth column by the burnup.

Burnup (MWd/t)	Pu-239 %	Pu-240 %	Pu-241 %	Pu-242 %	Pu produced (kg/t)	β (kg/MWd)
100	99.0	0.999	0.0112	4.10 e -5	0.095	9.5 e –4
200	98.0	1.96	0.0430	3.14 e -4	0.18	9.0 e –4
300	97.0	2.87	0.0931	0.00102	0.27	9.0 e –4
400	96.1	3.76	0.159	0.00232	0.35	8.8 e –4
500	95.2	4.61	0.240	0.00434	0.43	8.6 e –4
600	94.2	5.42	0.333	0.00727	0.51	8.5 e –4
700	93.3	6.21	0.437	0.0112	0.58	8.3 e –4
800	92.5	6.97	0.552	0.0161	0.65	8.1 e –4
900	91.5	7.70	0.675	0.0222	0.72	8.0 e –4
1000	90.8	8.41	0.806	0.0294	0.79	7.9 e –4

Appendix B: Estimated Capacity of Jiuquan Pilot Reprocessing Plant

The reprocessing plant at Jiuquan is said to have had two production lines and could process up to 400 kg of spent fuel daily, or 200 kg per line per day. The plant was said to operate "one or both lines continuously over 250 days per year." If both lines operated at full capacity for 250 days per year, the plant could reprocess 100 tonnes per year. If only one line was operating at a time, the plant could reprocess 50 tonnes per year. In these two cases the operation of the lines are perfectly correlated or anti-correlated.

One can also calculate the capacity of the plant assuming that the operation of the lines was independent of each other. If at least one of the production lines operated 250 days per year, then the probability that neither line was operating was 1-250/365 = 0.32. So:

$$(1-P_1)(1-P_2) = 0.32$$

where Pi is the probability that line i was operating. Assuming these probabilities were equal, this equation gives $P_1 = P_2 = 0.43$ and the total capacity of the plant is:

$$(P_1 + P_2)(365 \text{ days/year})(200 \text{ kg/day}) = 63 \text{ tonnes/year}$$

$$2 \times P \times 200\left(\frac{kg}{d}\right) \times 365\left(\frac{d}{yr}\right) = 63\left(\frac{te}{yr}\right)$$

Even if the probabilities are not equal, the total capacity is near 60 tonnes per year over a wide range of values of P_1 and P_2. For example, $P_1 = 0.2$ and $P_2 = 0.6$ give a total capacity of over 58 tonnes per year. This suggests that the capacity of the plant may have been considerably less than 100 tonnes per year.