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China's Uranium Enrichment Complex

Hui Zhang

Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, Cambridge, MA, USA

New public information allows a fresh estimate of China's current and under-construction uranium enrichment capacity. This paper uses open source information and commercial satellite imagery to identify and offer estimates of the capacity of China's 10 operating enrichment facilities, located at 4 sites, using centrifuge technology most likely based on adapting Russian technology. The total currently operating civilian centrifuge enrichment capacity is estimated to be about 4.5 million separative work units/year (SWU/year), with additional capacity estimated to be about 2 million SWU/year under construction. Also China could have an enrichment capacity of around 0.6 million SWU/year for non-weapon military uses (i.e., naval fuel) or dual use. These estimates are much larger than previous public estimates of China's total enrichment capacity. Further expansion of enrichment capacity may be likely since China will require about 9 million SWU/year by 2020 to meet the enriched uranium fuel needs for its planned nuclear power reactor capacity of 58 gigawatts-electric (GWe) by 2020 under its policy of self-sufficiency in the supply of enrichment services.

INTRODUCTION

China currently operates three enrichment plants, including Lanzhou uranium enrichment plant (Plant 504) in Gansu province, the Hanzhong uranium enrichment plant (Plant 405) in Shaanxi province, and Plant 814 in Sichuan province including facilities at Jinkouhe and Emeishan (see Table 1). The China National Nuclear Corporation (CNNC) has been the sole player responsible for enrichment services in China. However, this situation could change as the China General Nuclear Power Corporation (CGN) plans to provide such services both domestically and abroad.[1]

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Address correspondence to Hui Zhang, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, 79 John F. Kennedy Street, Box 134, Cambridge, MA 02138, USA. E-mail: hui_zhang@harvard.edu
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Table 1: China's uranium enrichment facilities.

Project	Capacity (million SWU/year)	Floor space (m^2)	SWU/m^2	Comments
Lanzhou GDP	0.2 (pre-1979), 0.3 (post-1979)	36,300	(8)	Operation in 1964; stopped HEU production in 1979; closed in 2000.
Lanzhou CEP 1 (Russia-supplied phase III)	0.5	25,600	20	Operation in July 2001. Russian 6th generation centrifuges.
Lanzhou CEP2 (demonstration project, domestic)	0.5	18,750	27	On 4 July 2008 started construction; operation in July 2010.
Lanzhou CEP3 (domestic)	0.5	18,750	27	Construction almost finished in 2010. Commission in December 2012.
Lanzhou CEP4 (domestic)	1.2	43,200	28	Started construction in 2013. By March 2015, half of building was completed.
Hanzhong CEP1 (Russian-supplied phase I)	0.2	8,800	23	Operation in February 1997. Russian 6th generation centrifuges. **IAEA Safeguards.**
Hanzhong CEP2 (Russian-supplied phase II)	0.3	16,500	18	Operation in January 1999. Russian 6th generation centrifuges. **IAEA Safeguards.**
Hanzhong CEP 3 (Russian-supplied phase IV)	0.5	16,200	31	Construction started in 2009 and conducted trials in 2011. Normal operation in 2013. Russian 7th and 8th generation centrifuges.
Hanzhong CEP 4 (North Expansion Centrifuge Project, domestic)	1.2	18,000	33 (for "double layers" case)	Construction permit on 4 January 2012. Trials in 2013. Normal operation in 2014.

Heping GDP/CEP? at Jinkouhe (Plant 814)	0.23 (pre-2004) 0.3-0.4 (post-2004)			Stopped HEU for weapons in 1987. Later operation for non-weapons military or dual uses.
Emeishan CEP 1 of Plant 814	0.8	29,700	27	Civilian purpose. Project initiated in 2008. Started construction around 2010–2011. Operation around 2013.
Emeishan CEP 2 of Plant 814?	(—0.8)	(—30,000)	(—27)	Earlier construction stage in 2014, still building in early 2015. Could be operational by 2016?
Emeishan CEP 3? (Plant 814)	0.25	9,450	27	Possible dual or military uses. Likely operational before 2009.

Note. Lanzhou is referred as Plant 504; Hanzhong is Plant 405; Plant 814 has enrichment sites at Jinkouhe and Emeishan.

China's uranium enrichment industry was initiated in the late 1950s to produce highly enriched uranium (HEU) for its nuclear weapon program.[2] China has produced HEU for weapons at two facilities: Lanzhou gaseous diffusion plant (GDP) which began operating in January 1964; and Heping GDP (Plant 814 at Jinkouhe), a "Third Line" facility that began operating in 1970.[3] It is believed that the Lanzhou and Heping GDPs stopped production of HEU in 1979 and 1987 respectively.[4] Lanzhou GDP was closed in 2000 and replaced by centrifuge enrichment plant (CEP) in 2001. Heping GDP is likely operating.[5]

In October 1969 China decided to build Plant 405 as a "Third Line" facility and worked on uranium enrichment technologies. China had conducted research and development (R&D) on centrifuge technology since 1958, and started to emphasize centrifuge work in the mid-1970s.[6] The major players include CNNC Research Institute of Physical and Chemical Engineering of Nuclear Industry at Tianjing and Plant 405.[7] Other academic units, including Tsinghua University, were actively involved as well.[8] China had intensified its centrifuge R&D efforts since the late 1970s and early 1980s.[9] In the mid-1980s, Plant 405 constructed and operated a pilot centrifuge facility under Project 405-1 which apparently was equipped with supercritical centrifuges.[10] It is reported AQ Khan gave Urenco centrifuge technology to China and helped build a centrifuge plant at Hanzhong around early 1980s.[11] However, it is not clear whether AQ Khan made significant contributions to the Project 405-1. As China deepened its "shift from military to civilian" in the nuclear industry during the late 1980s, the CNNC was eager to use the less-costly centrifuge enrichment technology to replace its gaseous diffusion technology. It did not work well, however, and China decided in the early 1990s to import a Russian centrifuge facility to replace the Project 405-1 as Project 405-1A.[12]

Under agreements in 1993, 1996 and 2008, China built Russian-supplied centrifuge facilities at the Hanzhong and Lanzhou plants in four phases for a total capacity of 1.5 million SWU/year. The Minatom/Tenex (Techsnabexport) supplied the centrifuges and technological aids, and the Chinese built and operate those enrichment facilities.[13]

As Russian centrifuge facilities were imported, CNNC started the localization process of the imported technology and designed its own centrifuges. This process accelerated China's active development of nuclear power since 2004. In 2007, CNNC started the project to construct its indigenous centrifuge facility at Lanzhou plant as a demonstration facility with a capacity of 0.5 million SWU/year, and it was commissioned in 2010.[14] Since then, China has significantly increased its enrichment capacity with domestically produced centrifuge facilities.

CNNC has declared that it maintains a policy of self-sufficiency in the supply of enrichment services.[15] In 2014, China needed about 3 million SWU (separative work units) annually of enrichment. In 2020 demand is expected to be about 9 million SWU/year.[16]

Many western sources argue that China is not currently able to meet its demand for separative work. For instance, the World Nuclear Association (WNA) estimated that China had a total capacity of 2.2 million SWU/year in 2014, including 1.5 million SWU/year from Russian-supplied centrifuges and 0.7 million SWU/year from indigenous facilities; and projected a total of 3 million SWU/year for 2015.[17] However, while there is considerable uncertainty, estimates based on satellite imagery, Chinese publications, and discussions with Chinese experts suggest that China is already operating enrichment facilities with a capacity that may be in the range of 4.5 million SWU/year. Moreover, another indigenous centrifuge capacity of about 2 million SWU/year is under construction, and may have the ability to add a million SWU/year of additional capacity each year. Furthermore, China could have an enrichment capacity of around 0.6 million SWU/year for non-weapon military uses or dual uses at dedicated enrichment facilities of Plant 814. These estimates are much larger than previous public estimates of China's total enrichment capacity.[18] According to CNNC's current plans, China will meet its uranium fuel requirements for its planned reactor capacity of 58 gigawatts-electric (GWe) by 2020 under its policy of self-sufficiency in the supply of enrichment services.

Finally, the CNNC nuclear experts address that the separation capacity of Chinese models is higher than Russian-supplied centrifuges, at least under the first three phases of the agreements.[19] However, some western experts are suspect of such a claim.[20] If Chinese models have the same number of shelves per stack as the Russian-supplied case, i.e., three,[21] (with the exception of Hanzhong 4, whose stack doubles the shelves of other facilities as discussed later), and there is a proportional relationship between enrichment capacity and the floor space of the main enrichment hall, then the Russian-supplied centrifuge facilities under the first three phases would produce about 20 SWU per square meter. The Chinese indigenous facilities produce an average of about 28 SWU per square meter (see Table 1), about a 40 percent increase from Russian's facilities under the first three phases.

It is reported those Russian-supplied centrifuges are using Russian 6th generation centrifuges. It has operated 8th generation centrifuges since 2003, and is operating 9th generation units.[22] Unlike previous generations using subcritical centrifuge technology, it has used supercritical technology since the 9th generation. Recently Russia is testing the 10th generation.[23]

It was estimated that the 7th and 8th generation machines have a separative capacity of 28 percent and 68 percent higher than the 6th generation model, respectively.[24] If a Chinese machine has a separative capacity about 40 percent higher than the 6th generation model, which may mean Chinese centrifuge is approaching the Russian model of 8th generation. In addition, the Hanzhong 3 (the fourth phase facility under the agreements) would produce about 30 SWU per square meter, about 50 percent higher than the 6th generation model. This likely means this fourth facility uses higher generation centrifuges than the 6th generation. Indeed, this is consistent with a recent report that "starting from 2009 Russia is supplying 7th and 8th generation centrifuges to China."[25] Given that the construction for Russian-supplied facilities under the first three phases were completed before 2001, and the Hanzhong CEP 3 (Russian-supplied phase IV) started construction in 2009, these Russian generation 7 and 8 centrifuges should be for Hanzhong CEP 3.

In June 2013, after it produced the LEU products at Lanzhou indigenously commercial centrifuge facility (Lanzhou CEP 3), CNNC enrichment experts further emphasized that the CNNC is developing a new generation of centrifuges that are more advanced, more economical and which have made significant progress in the key technology.[26]

LANZHOU URANIUM ENRICHMENT PLANT

Lanzhou enrichment plant (Chinese official name: CNNC Lanzhou Uranium Enrichment Co., Ltd., or Plant 504) includes a gaseous diffusion facility and centrifuge facilities under four projects (see Figure 1).

China has produced HEU for weapons in two complexes, the Lanzhou GDP and the Heping GDP. China also used these enrichment plants to produce HEU for its research reactors and LEU for naval reactors. The Lanzhou GDP began operations in 1964 and ended HEU production in 1979.[27] In 1980, it shifted to making LEU for civilian power reactors, and it was shut down on 31 December 2000.[28] During 2001 and 2002, the facility finished cleaning up radioactivity for decommissioning. Since then, the facility has kept the status of "sealed and maintenance."[29] It is estimated Lanzhou achieved a capacity of 0.18 million SWU/year by 1978, that increased to 0.3 million SWU/year during the 1980s. This GDP is estimated to have produced 1.1 million SWU between 1964 and 1979. This would be sufficient to produce about 6 tons of weapons-grade (90 percent enriched) HEU.[30]

As China deepened its nuclear shift from military to civilian during the late 1980s, CNNC was eager to use the less-costly centrifuge enrichment technology to replace its gaseous diffusion technology for providing enrichment services to its power reactors. Between 1991 and 1994 three PWRs with a total capacity of 2.3 GWe came on line with a demand of about 0.3 million SWU per year. However, China's development of its own centrifuge technology was slow and it imported technology as it pursued domestic capacity.

In 1993, China and Russia signed an agreement to build Russian-supplied centrifuge-enrichment facilities at the Hanzhong plant in two phases with a total of 0.5 million SWU/year. The modules began operating in 1997 and 1999, respectively. In 1995, China decided to build an additional eight reactors with

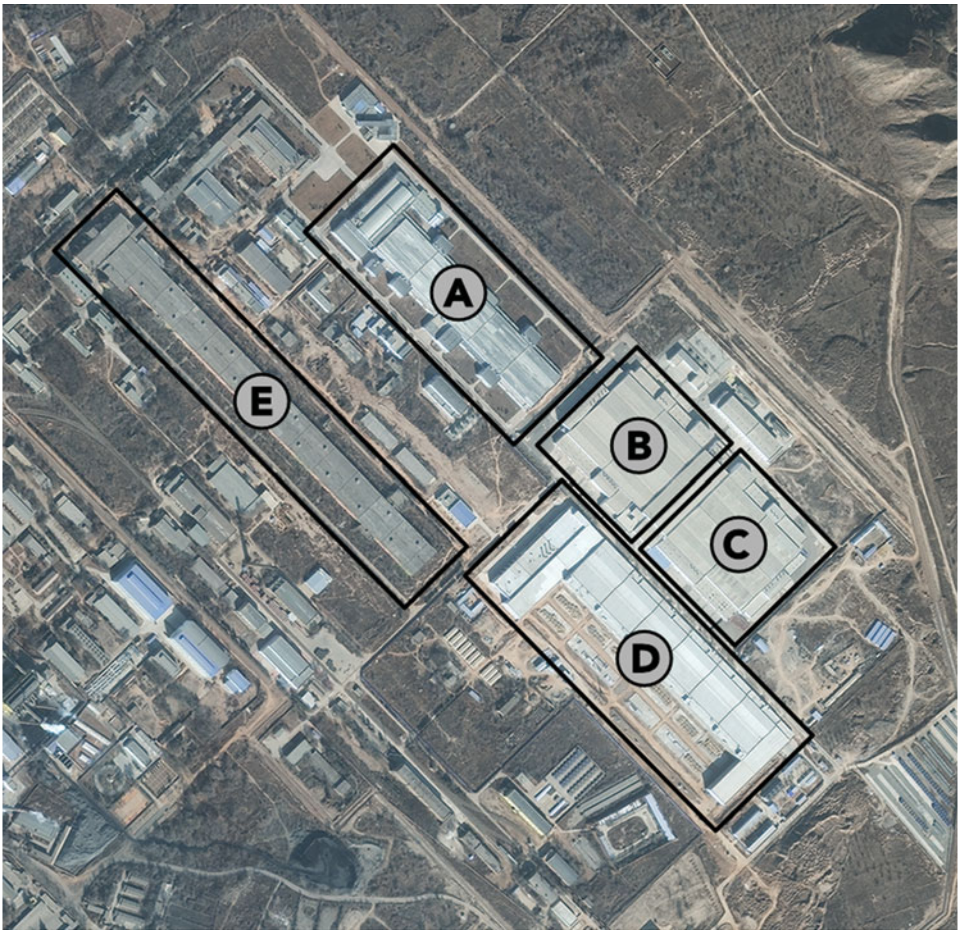

Figure 1: Lanzhou uranium enrichment plant. Label **A**: Lanzhou CEP 1 (Russian-supplied phase III); **B**: Lanzhou CEP 2 (Indigenous, demonstration project); **C**: Lanzhou CEP 3 (Indigenous); **D**: Lanzhou CEP 4 (Indigenous, under construction); **E**: Gaseous Diffusion Facility. Satellite image from 18 January 2015 (Coordinates: 36°08′53.30″ N/103°31′24.49″ E).

a total capacity of 6.9 GWe over the 1996–2002 period, including two domestic PWRs and two each purchased from France (PWRs), Canada (HWRs), and Russia (VVERs). Thus, China would operate nine PWRs with a total capacity of 7.7 GWe in early 2000s, which would require an enrichment capacity about 1 million SWU/year. Consequently, in 1996 China and Russia agreed to build a centrifuge facility at the Lanzhou enrichment plant with a capacity of 0.5 million SWU/year. The facility was commissioned in July 2001. Thus, those three phases with a total 1 million SWU/year could meet China's nuclear power development planned in 1990s. In addition, when China purchases foreign reactors, it often requires the foreign vendors to supply the first few loads. These arrangements save the Chinese both natural uranium and SWU. However, those saved SWUs account for a minor percentage of China's SWU production.[31] Additionally, it was reported that China occasionally exported SWUs to others, including sales of LEU to India in 1990s.[32]

As Russian centrifuge facilities were imported, CNNC designed its own centrifuges. CNNC's Research Institute of Physical and Chemical Engineering of the Nuclear Industry at Tianjing has been the major player in the design and development of the centrifuges. It produced its first centrifuge in 2002.[33] The process of development and mass production has accelerated since 2004 when China committed to active development of nuclear power.

China's indigenous centrifuge technology is likely based on the Russian technology. The Russian-supplied centrifuges, at least under the first three phases, were 6th generation units.[34] Russia's centrifuges have been subcritical through the 8th generation.[35] Each centrifuge is relatively small. It typically has a total length, including the top and bottom assembled bearing, of less than 1 meter, the rotor itself is about half a meter long, and the rotor diameter is at least four times smaller than the rotor length to remain subcritical.[36] The separative capacity of each 6th generation centrifuge is about 2.5 SWU/year. Russia's practice is to assemble these short subcritical centrifuges into stacks generally three to four shelves, up to seven layers high. Each level in a module has 20 machines comprising two rows of ten.[37]

In June 2007, CNNC formally started building Lanzhou Centrifuge Project 2 (the Lanzhou Centrifuge Commercial Demonstration Project) next to the Russia-supplied plant as an indigenous demonstration facility. On 4 July 2008, China National Nuclear Safety Administration (NNSA) issued the construction permit for the project.[38] CNNC Xinneng Nuclear Engineering Co., Ltd., was responsible for engineering design, construction, procurement, installation, and facility adjustment.[39] The demonstration facility began operating on 12 July 2010.[40] Its enrichment capacity is estimated at about 0.5 million SWU/year.[41]

Construction on Lanzhou Centrifuge Project 3 started sometime between late 2009 and early 2010. A satellite image on 3 October 2010 shows the main processing building almost completed. A satellite image from 16 November 2012 shows the building completed. The NNSA's annual report stated it conducted trial tests in 2012.[42] The CNNC reported it was commissioning in December 2012,[43] and in June 2013 CNNC announced it successfully produced the first batch of enriched uranium using its own centrifuges.[44] This commercial facility has a capacity of around 0.5 million SWU/year.[45]

Thus, CNNC announced in June 2013 that it had achieved complete independence in uranium enrichment technology (which means self-design, manufacturing, and operation of centrifuges) and had reached the internationally competitive level of uranium enrichment.[46]

On 8 January 2013, NNSA issued the construction permit for Lanzhou Centrifuge Project 4.[47] It is estimated that this larger commercial centrifuge facility will have a capacity of 1.2 million SWU/year.[48] As shown in Figure 1, the main processing building was half finished by early 2015. It is expected to be fully commissioned at the end of 2015. China plans to build another larger centrifuge facility with the similar capacity (Lanzhou Centrifuge Project 5), and other projects could follow.

CNNC experts state that China has the capability to build one centrifuge facility per year with 1 million SWU capacity.[49] They also emphasize that, from 2010 to 2020, China plans to increase its online enrichment capacity each year.[50] The head of the Lanzhou plant emphasized in June 2013 that this capacity would be able to meet China's entire demand by 2020.[51]

HANZHONG URANIUM ENRICHMENT PLANT

Hanzhong enrichment plant (CNNC Shaanxi Uranium Enrichment Co., Ltd. or Plant 405) has four centrifuge facilities (see Figure 2), three Russian-supplied centrifuge facilities as phase I, II and IV under the China Russian agreements, and a larger indigenous facility.

Plant 405 imported Russian-supplied centrifuge facilities in two phases under the 1993 China-Russia agreement. The first phase has a capacity of 0.2 million SWU/year and began operating in February 1997. The second phase, with a capacity of 0.3 million SWU/year, was commissioned in January1999.[52] A third phase with 0.5 million SWU/year was built in 2001 at Lanzhou under the 1995 agreement. After China adopted a policy of active development of nuclear power in the mid-2000s, China and Russia reached an agreement in May 2008 to construct another centrifuge facility with a capacity of 0.5 million SWU/year at Hanzhong as the fourth and final phase of their agreements. This unit started construction in 2009 and was completed in 2011. On 1 November 2012, NNSA accepted it for pre-feeding work and the facility began normal operation in 2013.[53]

The Hanzhong plant is also operating a much larger indigenous centrifuge facility (about 1.2 million SWU/year) described officially as the North Expansion Centrifuge Project, because it is located at the north of the Russian facilities. After the Lanzhou Demonstration Centrifuge Project (Lanzhou CEP 2) was commissioned in 2010, Hanzhong started its own indigenous centrifuge project. On 4 January 2012, it received permission for construction.[54] The project was completed in 2013 and began operating around 2014. Unlike the Lanzhou plant, that has enough land area to accommodate expansion, the available space at Hanzhong plant is limited. Hence, this indigenous facility is using stacks with double layers of Lanzhou CEPs.[55] The facility has two main enrichment buildings with a total capacity of about 1.2 million SWU/year.[56]

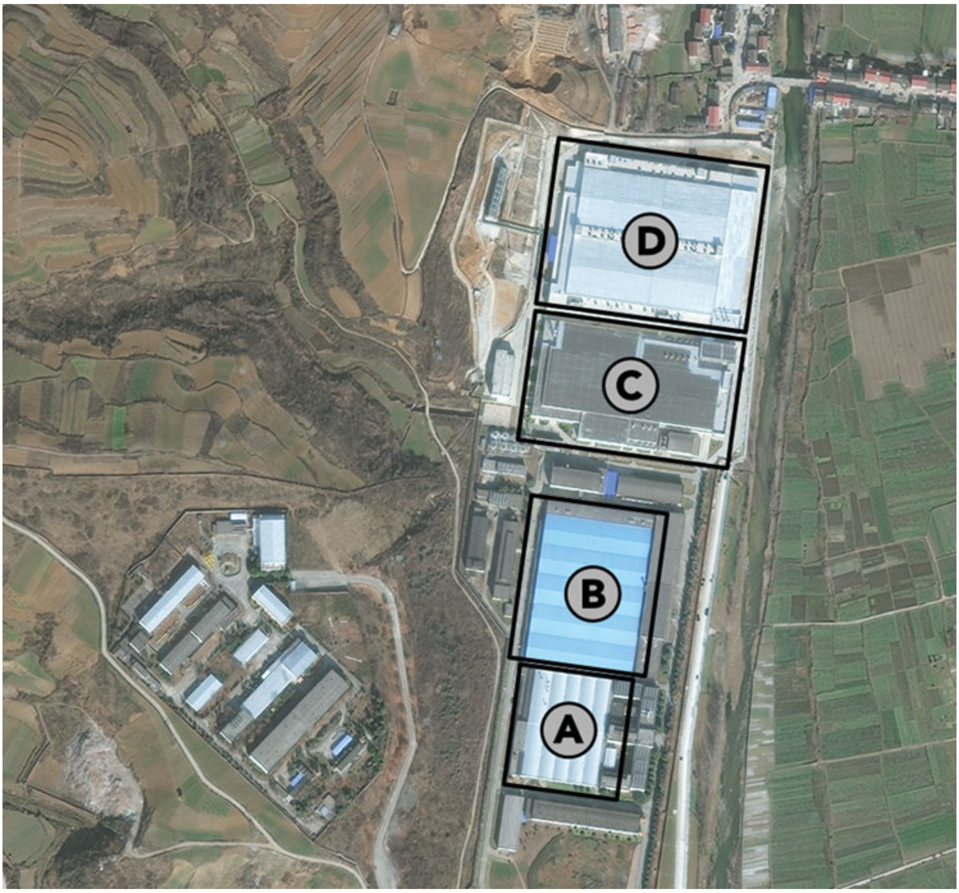

Figure 2: Hanzhong uranium enrichment plant. Label **A**: Hanzhong CEP 1(Russian-supplied phase I); **B**: Hanzhong CEP 2 (Russian-supplied phase II); **C**: Hanzhong CEP 3 (Russian-supplied phase IV); **D**: Hanzhong CEP 4 (Indigenous, North Expansion Project). Satellite image from 27 January 2013 (Coordinates: 33°15′47.70″ N/107°25′52.74″ E). © DigitalGlobe. Reproduced by permission of DigitalGlobe. Permission to reuse must be obtained from the rightsholder.

Under its Voluntary Offer Safeguards agreement, China offered all three Russian-supplied facilities as phase I and II at Hanzhong plant and phase III at Lanzhou plant for selection for IAEA safeguards. Due to a shortage of funds, the IAEA only selected the Hanzhong facilities.[57] The two Russian-supplied centrifuge facilities as Phase I and Phase II were placed under IAEA safeguards as part of a Tripartite Safeguards Agreement between the IAEA, Russia's Minatom, and China's Atomic Energy Authority (CAEA).[58] The fact that China offered IAEA inspectors access to Hanzhong and Lanzhou plants may indicate they are dedicated to pure civilian purposes.

Figure 3: Heping GDP at Jinkouhe, Sichuan. Satellite image from 28 September 2013 (Coordinates: 29°13′58.49″ N/103°03′49.95″ E). © DigitalGlobe. Reproduced by permission of DigitalGlobe. Permission to reuse must be obtained from the rightsholder.

URANIUM ENRICHMENT FACILITIES OF PLANT 814

CNNC enriches uranium at Plant 814 for both military and civilian purposes. Plant 814 is in Sichuan province and has enrichment facilities at Jinkouhe of Leshan city (Figure 3) and Emeishan city (Figure 4). Plant 814, often called Heping Uranium Enrichment Plant in the western media, is located at Heping Yuzu Township, near Jinkouhe of Leshan city.[59] However, as of July 2014, Plant 814 also operates centrifuge facilities near Emeishan city. Here, the Heping facility is referred to as Plant 814 at Jinkouhe, and Emeishan facility as Plant 814 at Emeishan city.

Figure 4: Emeishan CEP 1 and CEP2 of plant 814 at Shuangfu near Emeishan city. Label **A**: Emeishan CEP 1 (operational); **B**: Emeishan CEP 2 (under construction); **C**: space ready for additional CEP project. Satellite image from 5 October 2014 (Coordinates: 29°40′38.33″ N/103°32′04.65″ E). © DigitalGlobe. Reproduced by permission of DigitalGlobe. Permission to reuse must be obtained from the rightsholder.

The Heping gaseous diffusion plant began operating on 25 June 1970 (earlier than its previously assumed startup in 1975).[60] It is believed to have stopped producing weapons-grade HEU in 1987 as a result of China's military-to-civilian conversion policy.[61] Chinese publications indicate that the facility continued operation, however.[62] China still needs enriched uranium products for other non-weapon military uses including LEU for naval reactors, HEU for tritium production reactors and some research reactors, and Lanzhou and the Hanzhong centrifuge plants, which appear to be dedicated to civilian purposes. The fact that China still uses the code name (Plant 814) suggests that it is more sensitive than the Lanzhou and Hanzhong plants that have official public names, replacing previous code names of Plant 504 and Plant 405 respectively. The Heping facility therefore may be military or dual use.

The Heping plant produced HEU from 1970 to 1987 and is estimated to have produced 3 million SWU, sufficient for about 15 tons of weapons-grade (90 percent enriched) HEU.[63] Together, the Lanzhou and Heping gaseous diffusion plants therefore produced roughly 4.1 million SWU, enough to make about

21 tons of weapons-grade HEU. Taking into account the separative work consumed by research and naval reactors, tritium production reactors, in nuclear tests, and waste, the total amount of weapons-grade HEU in China's stockpile is estimated to be 18±4 tons.[64]

The Heping GDP was estimated to have a capacity of 230 tSWU/year before 1987.[65] However, new information indicates that the output of the facility was increased 45 percent around 2004. Consequently, Heping GDP could have a capacity between 0.3–0.4 million SWU/year. Moreover, it is reported the Plant 814 was renovated and upgraded around 2006.[66]

In addition, to meet China's increasing SWU demands, it appears that Plant 814 built a larger commercial centrifuge facility (Emeishan CEP1) near Emeishan city. Based on the city's official documents, the centrifuge project (referred as Plant 814 Centrifuge Project 1, which may indicate other projects will follow) was planned to start in 2008.[67] While there is no public information on the specific location, based on the satellite image (Figure 4) Plant 814 could be at the town of Shuangfu near Emeishan city.

The Emeishan CEP1 started construction around 2011. This facility may have started operating around 2013. This facility could have a capacity around 0.8 million SWU/year.[68]

Based on a satellite image taken on 5 October 2014 (Figure 4), another CEP project (Emeishan CEP2) seems to be an early stage of construction. Based on a satellite image (taken on 16 February 2015) and visible on Google Earth, significant progress was made. It generally takes about two years from construction to commissioning for a centrifuge enrichment facility with a capacity around 1 million SWU/year, including one year for building enrichment hall and centrifuges installations, and one year for trial tests, adjustment of facility, and review and approval by NNSA. Thus, this facility could be commissioned around 2016. Given that the total square footage of the enrichment building is estimated to be similar to that of the Emeishan CEP1, Emeishan CEP2 is assumed to have a capacity around 0.8 million SWU/year. In addition, the satellite image shows that the space alongside the CEP1 is ready for an additional CEP.

Due to features such as a large roof and cooling system, another smaller facility (Emeishan CEP3) near the larger commercial centrifuge plant (Figure 5), could be a centrifuge facility. The satellite image shows the facility was completed by March 2009. The size of the roof is half that of Lanzhou Centrifuge Project 3 (0.5 million SWU/year), therefore it is estimated that the facility could have an enrichment capacity of 0.25 million SWU/year. As an assumption, this smaller CEP could have been built as a pilot domestic CEP around 2006. It may be the "technology update and renovation" for Plant 814 that was reported around 2006.[69] Given that China had already produced a single centrifuge in 2002, and began to accelerate commercialization activities in 2004, and Lanzhou Commercial Demonstration Centrifuge Project started

Figure 5: Emeishan CEP3 of plant 814 near Emeishan city. Label **A:** Enrichment building; **B:** Cooling towers. Satellite image from 5 October 2014 (Coordinates: 29°38′38.70″ N/103°29′25.12″ E). © DigitalGlobe. Reproduced by permission of DigitalGlobe. Permission to reuse must be obtained from the rightsholder.

in 2007, it would have been reasonable to set up a small (or pilot) centrifuge facility around 2006. This is consistent with China's model to develop a nuclear program through piloting, demonstration and commercialization.

Finally, given that the site is isolated from the public transportation system and has a dedicated road and entrance, it is most likely a facility for dual or military uses.

PURSUING SELF-SUFFICIENT SWU SUPPLY

In addition to its centrifuge facilities at Lanzhou, Hanzhong, and Emeishan, CNNC had planned until June 2013 (initiated in February 2012) to build a large-scale uranium processing complex in Heshan of Guangdong province. The Heshan project was to be a 40 billion Yuan ($6 billion) processing complex for uranium purification and conversion, uranium enrichment, and fuel fabrication. It was reported the nuclear fuel products would meet half of the demand of China's nuclear power in 2020,[70] which would mean the enrichment capacity could be around 5 million SWU/year. One lead of CGN pointed out the capacity was 7 million SWU/year.[71]

After a major protest by approximately a thousand people, the Heshan project was cancelled in July 2013.[72] The protestors voiced concerns about public health and environmental costs. They complained the project lacked an adequate environmental impact assessment and that the ten-day public consultation on social stability was too short. Several local governments are currently competing to host the facility however, because they believe the project will promote economic development.[73] Indeed, CNNC and CGN have an active plan to expand the nuclear fuel complex.[74]

In addition, the Lanzhou and Emeishan plants still have space and plan to expand their enrichment capacities. Considering CNNC's current operational capacity of 4.5 million SWU/year, 1.2 million SWU/year under construction at Lanzhou, about 0.8 million SWU/year under construction at Shuangfu site near Emeishan city, and about 7 million SWU/year at planned new sites, it would be easy for China meet its enrichment requirements, about 9 million SWU/year by 2020. China's tendency to require foreign vendors to supply the first and a few subsequent loads save Chinese both natural uranium and SWU.[75] CGN's recent deal with Kazakhstan to import enriched product would save additional SWU.[76]

Therefore, China's SWU capacity may exceed its domestic requirements through 2020. This is consistent with CNNC's policy of "meeting its domestic demand and targeting the international markets" to supply enrichment services.[77] China has been pursuing full independence in its enrichment activities including R&D, engineering, manufacturing and operations. As CNNC chief engineer for enrichment technology, Lei Zengguang, emphasized in an interview in June 2013, to secure China's nuclear power development, "enrichment technology must be completely independent. So far, China has had the centrifuge manufacturing capacity that can fully meet the subsequent need of nuclear power development." While it prioritizes domestic supply of SWU, CNNC will gradually expand its foreign markets and make China's nuclear fuel industry become internationally competitive."[78]

CONCLUSIONS

While considerable uncertainty remains, based on satellite imagery, Chinese publications, and discussions with Chinese experts, the evidence suggests that China is already operating enrichment facilities with a capacity that may be in the range of 4.5million SWU/year, have an additional capacity estimated to be about 2 million SWU/year under construction, and may have the ability to add a million SWU/year of additional capacity each year. China has a lot more enrichment capacity now than was previously believed, and continues to expand.

For instance, the World Nuclear Association estimates that China has a total of 2.2 million SWU/year. Moreover, China has enough enrichment capacity to meet its nuclear fuel requirements for power reactors for the coming decade and beyond. China will have excess enrichment capacity and will become a net exporter of commercial enrichment services. The practice of China's enrichment development is consistent with China's pursuing policy of self-sufficiency and "targeting the international markets" in the supply of enrichment services.

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8. Li et al., *China Today: Nuclear Industry,* 390.

9. Communications with CNNC nuclear experts, October 2014.

10. See, e.g., Huang Wenhui and Qian Xikang, "Persons of Tsinghua University in Qinbashan," *China Youth Science and Technology* 12 (2003), in Chinese, http://wuxizazhi.cnki.net/Search/QNKJ200312016.html; also Liang Guangfu, then-deputy chief engineer of Plant 405, "To Cast the Light of the Century by Youth," talk at Tsinghua University, fall 2005, http://www.newsmth.net/nForum/#!article/TsinghuaCent/353223.

11. See, e.g., R. J. Smith and J. Warrick, "Pakistani Nuclear Scientist's Accounts Tell of Chinese Proliferation," *The Washington Post* 13, November 2009, http://www.washingtonpost.com/wp-dyn/content/article/2009/11/12/AR2009111211060.html).

12. Communications with CNNC nuclear experts, October 2014.

13. Communications with CNNC nuclear experts, October 2014.

14. Communications with CNNC nuclear experts, July 2013. Also see "China's Indigenous Centrifuge Enrichment Plant," *Nuclear Intelligence Weekly* 25 October 2010, http://www.energycompass.com/pages/eig_article.aspx?DocId = 691792.

15. Li Guanxing, "Status and Future of China's Front-end of Nuclear Fuel Cycle," *China Nuclear Power* 3, (2010), in Chinese.

16. Assuming China's total nuclear capacity is linearly increased from 20 GWe in 2014 to 58 GWe by 2020 (based on China's current official plan through 2020), China's nuclear growth will be contributed by PWRs and an annual requirement of SWU per GWe PWR is about 129 ton-SWU (1000 kg-SWU). Producing the initial core for each PWR will require the equivalent of about three times the annual SWU requirement. Consequently, it estimates the annual SWU requirement is increased to about 9 million SWU in 2020 from about 3 million SWU in 2014. To estimate SWU demand in 2014, we consider the total nuclear capacity of 20 GWe in 2014 which includes adding new 3 GWe PWRs to the total of 17 GWe in 2013, thus it needs to cover SWU for those new cores. In addition, the total nuclear capacity of 20 GWe needs to subtract about 1.5 GWe of the two Candu reactors (which do not need SWU).

17. World Nuclear Association: Uranium Enrichment (Updated April 2015), http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/.

18. See, e.g., World Nuclear Association: Uranium Enrichment**;** P. Chaffee and K. F. Wong, "China's Indigenous Capacity May be Double Previous Estimates," *Nuclear Intelligence Weekly* 1 (March 2013): 3–4; Jeffrey Lewis, "China's New Centrifuge Plants," *Arms Control Wonk,* 17 September 2013, http://lewis.armscontrolwonk.com/archive/6826/chinas-new-centrifuge-plants. Those previous public estimates did not account for new centrifuge facilities at Emeishan, and they incorrectly underestimated the enrichment capacity of domestic CEPs at the Hanzhong and Lanzhou plants. For instance, Hanzhong CEP 4 has a capacity about 1.2 million SWU/year (versus the estimated 0.25 million SWU/year).

19. Communications with CNNC nuclear experts, October 2014.

20. See, e.g., Lewis, "China's New Centrifuge Plants."

21. In general, each stack has three or four shelves, and can be up to seven shelves (see Oleg Bukharin, "Russia's Gaseous Centrifuge Technology and Uranium Enrichment Complex," Working Paper, Program on Science and Global Security Woodrow Wilson School of Public and International Affairs Princeton University, January http://www.partnershipforglobalsecurity-archive.org/Documents/bukharinrussianenrichmentcomplexjan2004.pdf). Considering Hanzhong 4 modular doubles the shelves of others, thus it is assumed the other models have three shelves.

22. World Nuclear Association, Russia's Nuclear Fuel Cycle, Updated February 2015. http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/Russia–Nuclear-Fuel-Cycle/#Enrichment.

23. "Russia 1st to Test 10th Generation Uranium Enrichment Centrifuges," 27 April 2015. http://rt.com/news/253245-rosatom-uranium-enrichment-centrifuge/.

24. It is estimated that the 6th-, 7th- and 8th-generation machines have a separative capacity of 2.5, 3.2, and 4.2, respectively. See, e.g., David Albright et al, *Plutonium and*

Highly Enriched Uranium 1996 (Oxford University Press, 1997). Bukharin, Russia's Gaseous Centrifuge Technology and Uranium Enrichment Comple*x*.

25. "Russia 1st to test 10th Generation Uranium Enrichment Centrifuges."

26. Lei Zengguang, "China has accomplished a complete self-independency of uranium enrichment technology" (in Chinese), 25 June 2013. http://news.china.com.cn/tech/2013-06/25/content_29217256.htm.

27. Zhang, *Global Fissile Material Report 2010*.

28. Jing Yongyu et al., Economic Analysis on Decommissioning of Lanzhou Gaseous Diffusion System, Proceedings of Workshop on Recycling Economics (in Chinese), 1 July 2008.

29. Jing, et al., Economic Analysis on Decommissioning of Lanzhou Gaseous Diffusion System.

30. Zhang, *Global Fissile Material Report 2010*.

31. Hui Zhang, *China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs.* (Cambridge, MA: Report for Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School), August 20, 2015. http://belfercenter.ksg.harvard.edu/files/chinasuraniumenrichmenntcapacity.pdf

32. "Russia First off the NSG Block, Says it Will Supply Fuel to Tarapur," *Express News Service*: New Delhi, 14 March 2006. http://archive.indianexpress.com/news/russia-first-off-the-nsg-block-says-it-will-supply-fuel-to-tarapur/463/0

33. Lei Zengguang, "China has Realized its Independent Uranium Enrichment' (in Chinese), 17 May 2013. http://www.caea.gov.cn/n16/n1223/542004.html.

34. World Nuclear Association report indicates the Russian-supplied centrifuges were 6th generation centrifuges (World Nuclear Association, China's Nuclear Fuel Cycle, Updated February 2015. http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China–Nuclear-Fuel-Cycle/). However, a recent report indicates the Hanzhong CEP 3 (Russian-supplied phase IV) use Russian generation 7 and 8 centrifuges (see "Russia 1st to Test 10Gen Uranium Enrichment Centrifuges."

35. Centrifuges are either "subcritical" or "supercritical." A subcritical centrifuge rotor has a length to diameter ratio such that it runs optimally at an angular velocity below the first fundamental flexural critical frequency. At these critical frequencies, the rotational energy of the spinning rigid body is transferred into large displacements from the axis of rotation, breaking the rotor unless mechanical actions are taken to reduce the displacement amplitudes. A supercritical centrifuge operates above the first critical frequency, and avoids damaging effects associated with resonances by mechanical methods such as damping mechanisms and bellows (flexible joints connecting rotor tubes together that act like a spring).

36. See, e.g., Albright et al, *Plutonium and Highly Enriched Uranium*, 106–107.

37. Oleg Bukharin, "Russia's Gaseous Centrifuge Technology and Uranium Enrichment Complex."

38. NNSA, Annual Report 2008.

39. "Integrating Resources Advantages to Build Demonstration Project of Plant 504," China Nuclear Industry (in Chinese), No.12, 2008.

40. CNNC, "1995 to 2000" in "60 Events in 60 Years," http://www.cnnc.com.cn/publish/portal0/tab904/info88022.htm; also, NNSA, Annual Report 2010.

41. See "China's Indigenous Centrifuge Enrichment Plant." *Nuclear Intelligence Weekly*, 25 October 2010. http://www.energycompass.com/pages/eig_article.

aspx?DocId=691792. This facility was reported to have a capacity of 0.5 million SWU/year. Also, it is consistent with communications with Chinese nuclear experts in July 2013.

42. NNSA, Annual Report 2012.

43. CNNC, "1995 to 2000;" Li Jin, "Chin's Uranium Enrichment Centrifuges Achieved Industrial Application," *Workers' Daily* (in Chinese), 1 March 2013, see also, http://news.xinhuanet.com/tech/2013-03/01/c_124402348.htm

44. Zhang Xiaobo, "China Develops Own Tech to Enrich Uranium," *Global Times,* 25 June 2013. http://www.globaltimes.cn/content/shtml#.UclTyj7k5YQ. Also, NNSA, Annual Report 2013.

45. Assuming this facility has the same capacity as that of the demonstration project given that both have the same total footages of the roof. This estimate is consistent with communications with Chinese nuclear experts in July 2014.

46. Yu Siluan, reporter, "A completely independent uranium enrichment technology has achieved industrialization and is developing a new generation of centrifuges," *People's Daily* (in Chinese), 2 June 2013. http://paper.people.com.cn/rmrb/html/2013-06/22/nw.D110000renmrb_20130622_6-01.htm.

47. NNSA, Annual Report 2013.

48. As Table 1 shows, its total footages of the enrichment building is about 2.3 times of that of Lanzhou CEP 3 which has a capacity of 0.5 million SWU/year. This estimate is also consistent with communications with Chinese nuclear experts in February 2015.

49. Kang Rongyuan and Gong Yufeng, Suggestions on China's Nuclear Fuel Development and Strategy, 4 February 2013, www. China-nea.cn/html/2013-02/25688.html.

50. Li Guanxing, "Status and Future of China's Front-end of Nuclear Fuel Cycle."

51. Zhang, "China Develops Their own Technology to Enrich Uranium."

52. Wang, "60 Years of New China's Nuclear Energy Development Key Events."

53. NNSA Annual Report 2012 and 2013.

54. NNSA Annual Report 2012.

55. Communications with Chinese nuclear experts, November 2014.

56. It is estimated, based on a comparison between its total roof footages of enrichment buildings with that of Lanzhou CEP2, and considering the facility uses stacks doubling layers of Lanzhou facilities. Also, this estimate is consistent with Communications with Chinese nuclear experts in November 2014.

57. Communications with CNNC nuclear experts, October 2014.

58. A. Panasyuk, A. Vlasov, S. Koshelev, T. Shea, D. Perricos, D. Yang, and S. Chen, "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," IAEA-SM-367/8/02 (IAEA, 2001).

59. Zhang, *Global Fissile Material Report* 2010.

60. See Wang, "60 Years of New China's Nuclear Energy Development Key Events." Also available at: http://www.china-nea.cn/html/2009-11/4239.html.

61. Zhang, *Global Fissile Material Report 2010*.

62. See, e.g., Cheng, "Plant 814: the New era of 'Small Yan'an."

63. For the new operation period from 1970 to 1987, based on the following assumptions: a) From 1970–74, a linear increase from 50,000 to 100,000 SWU per year at a tails assay of 0.3 percent; b) From 1975–79, a linear increase from 100,000 to 230,000

SWU per year at a tails assay of 0.3 percent; c) From 1980–87 the plant operated at 230,000 SWU per year at a tails assay of 0.3 percent. Consequently, the Heping GDP would have produced 3 million SWU, sufficient to produce about 15 tons of HEU.

64. This is an update from the earlier estimate of 16±4 tons (see Zhang, *Global Fissile Material Report 2010*). The major update is incurred by the operation started date of Heping GDP.

65. Zhang, *Global Fissile Material Report 2010*.

66. Cheng, "Plant 814: the New era of 'Small Yan'an." However, it is not clear if the "upgrade and renovation" of Plant 814 addressed only the Heping GDP (given that Plant 814 could have Emeishan CEP3 at that time). If it meant only for Heping GDP, it may indicate a replacement by CEP. CNNC experts also emphasized in 2009 that China had finished the transition from gaseous diffusion technology to gas centrifuge technology (see Li, "Status and Future of China's Front-end of Nuclear Fuel Cycle.") which may indicate Heping GDP could have been replaced by a centrifuge facility by late 2000s. However, there is no convincing evidence to confirm this.

67. "Development and Reform Bureau of Emeishan City, Key Work Points in 2008," March 18, 2008. http://www.leshan.gov.cn/UploadFile/UploadFile/emeishan/20084159272366099.doc. This governmental document addressed that one key work point is to assist the Plant 814 centrifuge project at Emeishan, including land acquisition and other preparatory work, and strive to start construction within 2008.

68. Its total footage of the enrichment building is about 1.6 times that of Lanzhou CEP 3 which has a capacity of 0.5 million SWU/year. This estimate is also consistent with communications with Chinese nuclear experts in June 2015.

69. See Cheng, "Plant 814: the New era of 'Small Yan'an."

70. Liu Qingshan, "Waiting for Knowing the East Wind: Heshan Setback," *China SOE* (2014) 28–29. It was based on an interview with CNNC president Sun Qin. The China SOE (State Owned Enterprise) is run by the State Owned Assets Supervision and Administration Commission of the State Council.

71. See details P. Chaffee, "Fuel Cycle: CNNC-CGN Guangdong Fuel Plant Rises from the Ashes."

72. Liu, "Waiting for Knowing the East Wind: Heshan Setback."

73. Communications with CNNC nuclear experts, October 2014.

74. See P. Chaffee, "Fuel Cycle: CNNC-CGN Guangdong Fuel Plant Rises From the Ashes."

75. See, e.g., AREVA will supply fresh fuel for 15 years for its two exported EPRs at the Guangdong Taishan nuclear power plant; Westinghouse will supply the first loads for its four AP1000 reactors sold to China. Enriched uranium products for the first four AP1000 reactors will be supplied by Tenex of Russia from 2010 to 2021, under the 2008 agreement; Urenco supplies 30 percent of the enriched uranium for the two Daya Bay reactors in Guangdong; Russia's TVEL will supply the fuel for Tianwan 3& 4 (two VVERs) until 2025. See details in Zhang and Bai, "China's Access to Uranium Resources."

76. P. Chaffee and Kevin Pang, "Washington Spot Price Weakens Again While Producers Shrug"

77. Li, "Status and Future of China's Front-end of Nuclear Fuel Cycle."

78. Yu, "A completely independent uranium enrichment technology: has achieved industrialization and is developing a new generation of centrifuges."