

PROJECT ON MANAGING THE ATOM

CHINA'S URANIUM ENRICHMENT CAPACITY:

RAPID EXPANSION TO MEET COMMERCIAL NEEDS

HUI ZHANG



HARVARD Kennedy School

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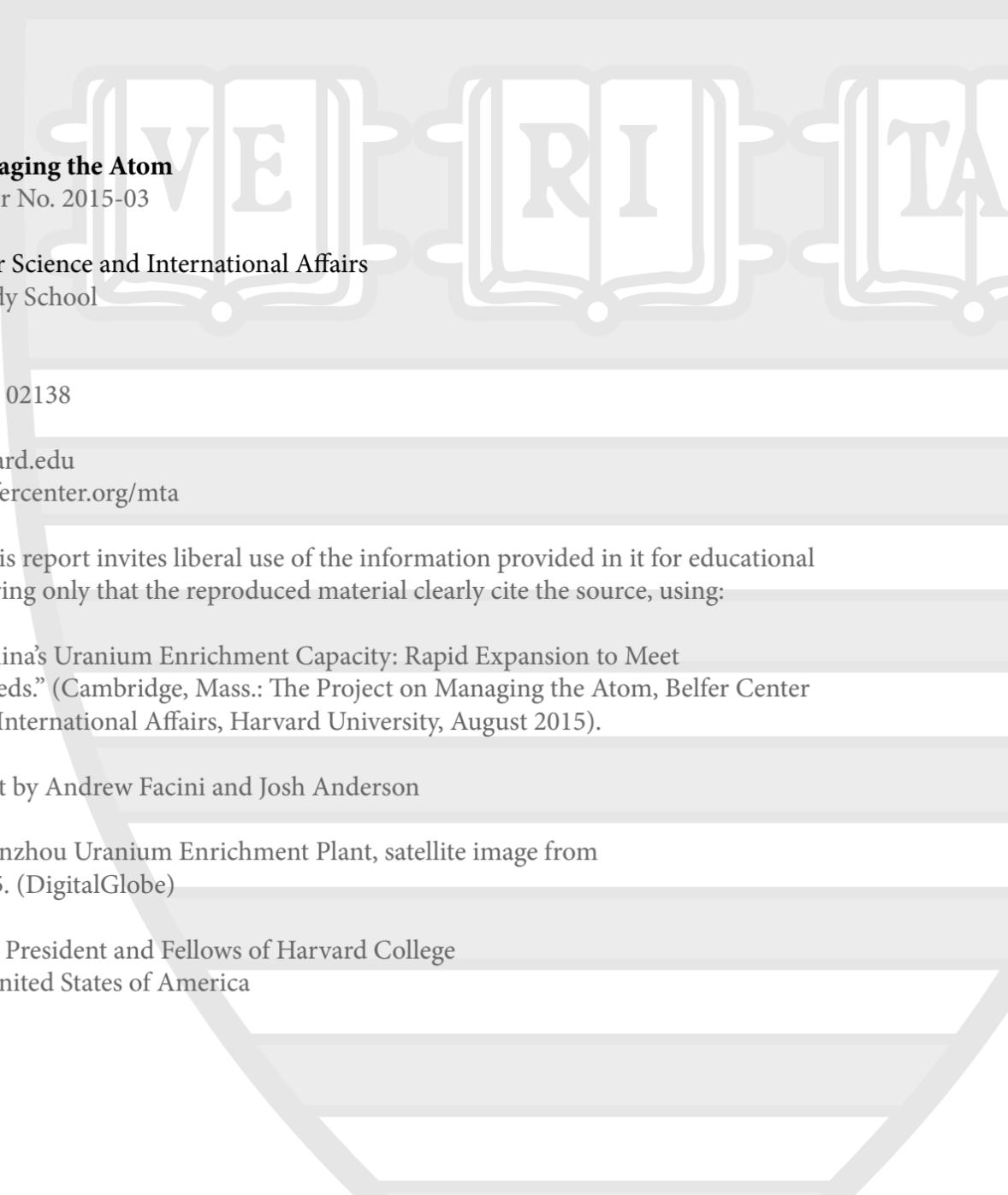
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Belfer Center for Science and International Affairs
Harvard Kennedy School

79 JFK Street
Cambridge, MA 02138
617-495-4219
atom@hks.harvard.edu
<http://www.belfercenter.org/mta>

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ABOUT THE AUTHOR

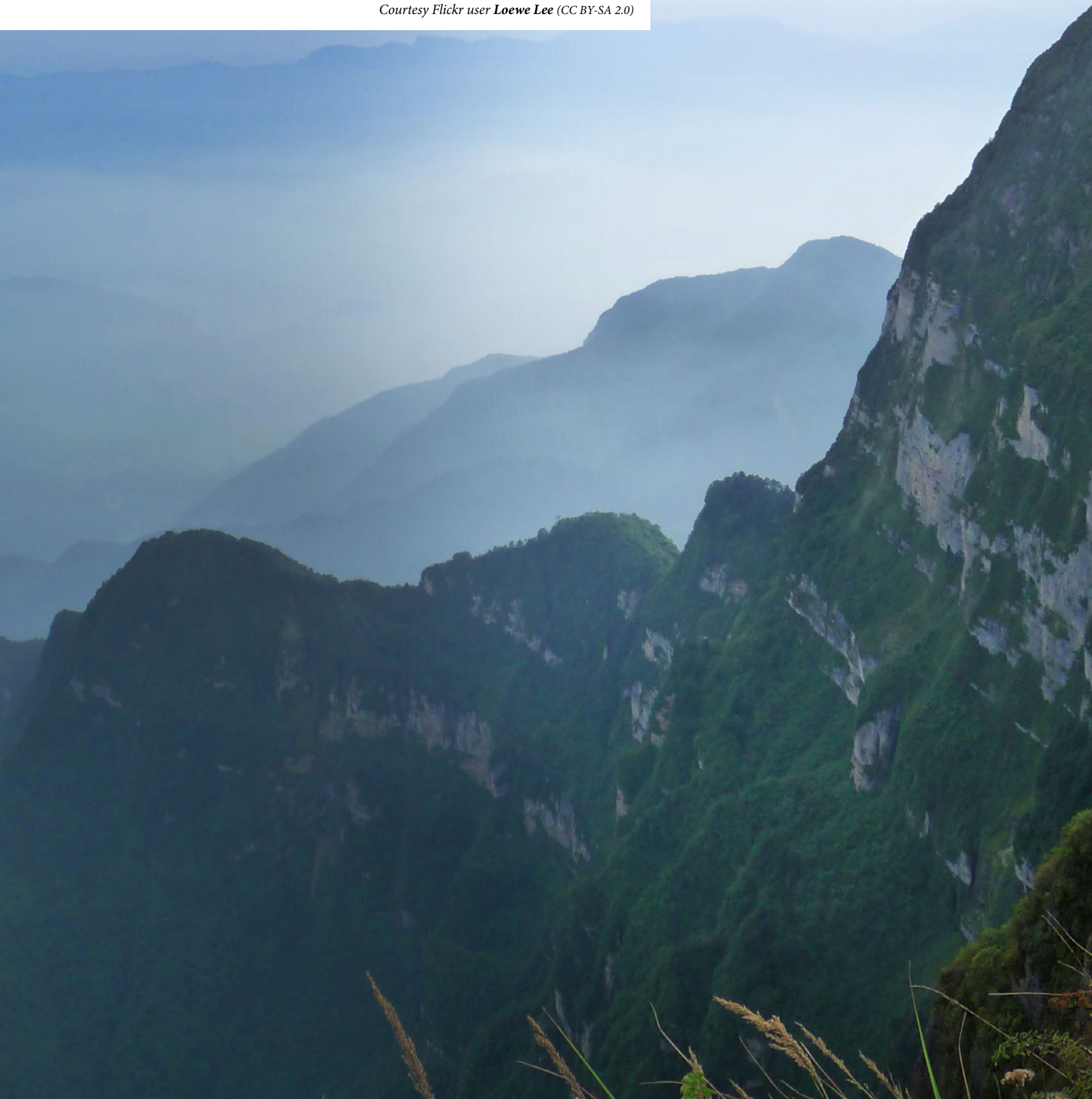
Hui Zhang is a Senior Research Associate with the Project on Managing the Atom in the Belfer Center for Science and International Affairs at Harvard University's John F. Kennedy School of Government, where he is leading a research initiative on China's nuclear policies. His research interests include verification techniques of nuclear arms control, the control of fissile material, nuclear terrorism, nuclear safeguards and non-proliferation, nuclear fuel cycle and reprocessing policies, and China's nuclear future. Dr. Zhang is the author of a number of technical reports and book chapters, and dozens of articles in academic journals and the print media including *Science and Global Security*, *Arms Control Today*, *Bulletin of the Atomic Scientists*, *Disarmament Diplomacy*, *Disarmament Forum*, *The Nonproliferation Review*, *Washington Quarterly*, *Journal of Nuclear Materials Management*, and *China Security*.

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Looking out over Mount Emei (峨眉山), a UNESCO World Heritage Site located about 15 miles from the rapidly expanding uranium enrichment plant outside Emeishan City.

*Courtesy Flickr user **Loewe Lee** (CC BY-SA 2.0)*





EXECUTIVE SUMMARY

China leads the world in the pace of nuclear development and in new reactor construction. By May 2015, China had 27 power reactors (24 gigawatts-electric (GWe)) in operation with 24 units under construction. In October 2012, after comprehensive post-Fukushima safety inspections of all plants in operation and under construction, China's State Council issued a new "Medium- and Long-Term Nuclear Power Development Plan (2011-2020)." China expects its total nuclear capacity to be 58 GWe with another 30 GWe under construction by 2020, and much more is under consideration for the coming decades.

To meet the expected rapid increase in uranium requirements, the central government has adopted a uranium acquisition strategy that combines domestic production, overseas exploitation, and purchases on the world market. China has recently secured a huge amount of overseas uranium resources—about three times the size of its own identified uranium resources. More could easily be added, which would make for more than enough to meet the requirements of the country's most ambitious nuclear energy plan through 2050.

But how and where will China enrich the uranium needed to fuel its nuclear power plants—predominantly pressurized water reactors (PWRs)? The China National Nuclear Corporation (CNNC)—the entity that is currently solely responsible for enrichment services in China—has said it maintains a policy of "self-sufficiency" in the supply of enrichment services. In 2014, China needed about 3 million SWU (separative work units) of enrichment. By 2020, demand is expected to be about 9 million SWU.

Many Western sources estimate that China's current enrichment capacity will not be able to meet currently projected demand. For instance, the World Nuclear Association (WNA) estimated in April 2015 that China had a total enrichment capacity of 2.2 million SWU/year in 2014 and projected a total of 3 million SWU/year in 2015. 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 in the range of 4.5 million SWU/year, and may have the ability to add 1 million SWU/year of additional capacity each year.

China may have much more enrichment capacity now than previous estimates suggested, and even more is planned. Recent information offered in this report suggests that 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. In practice, the development of China's enrichment capabilities has been consistent with the policies of pursuing "self-sufficiency" and "targeting the international markets" in the supply of enrichment services.

Major Developments in China's Uranium Enrichment Capacity

China currently operates three enrichment plants: the Lanzhou uranium enrichment plant (Plant 504) in Gansu province, Hanzhong uranium enrichment plant (Plant 405) in Shaanxi province, and Plant 814 in Sichuan province, which has facilities at Jinkouhe and Emeishan.

The Military Origins of Chinese Enrichment: China's uranium enrichment industry was initiated in the late 1950s to produce highly enriched uranium (HEU) for the country's nuclear weapons program. China is believed to have ended HEU production for weapons in 1987. China produced HEU for weapons at two facilities: the Lanzhou gaseous diffusion plant (GDP) and Heping GDP (the Jinkouhe facility of Plant 814). 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. Since 1980, it shifted to making LEU for civilian power reactors, and was shut down in 2000 and replaced by a centrifuge enrichment plant (CEP) after 2001. The Heping plant produced HEU for weapons from 1970 to 1987. Since 1987, the plant is reported to have continued operations for non-weapons military or dual uses.

The Emergence of Civilian Enrichment in China: As China deepened its "shift from military to civilian" in the nuclear industry during the late 1980s, CNNC was eager to adopt less-costly centrifuge enrichment technology to replace its gaseous diffusion plants. However, development of its own centrifuges for commercial use was slow. China decided to

follow the same technology development strategy it had pursued for acquiring advanced power reactor technology: importing foreign technology and then localizing it.

In 1993, China and Russia signed an agreement to build Russian-supplied centrifuge facilities at the Hanzhong plant in two phases with a combined reported capacity of 0.5 million SWU/year. In 1996, the two countries agreed to build another centrifuge facility at the Lanzhou enrichment plant also with a capacity of 0.5 million SWU/year, as the third phase in the acquisition of Russian centrifuge facilities. After China adopted a policy of “active development” of nuclear power in the mid-2000s, it reached an agreement with Russia in 2008 on the construction of another centrifuge facility with a capacity of 0.5 million SWU/year at the Hanzhong plant as the fourth and final phase. Altogether, the four phases of Russian-supplied centrifuge facilities account for a capacity of 1.5 million SWU/year, as widely reported.

The Indigenization of Chinese Centrifuges: As Russian centrifuge facilities were imported, CNNC started localization of the imported technology and designed its own centrifuges. It produced its first centrifuge in 2002 and then began the industrialization of centrifuge technology for production. The process was accelerated in accordance with China’s adoption of a policy of “active development” of nuclear power in 2004. In 2007, CNNC started a project to construct an indigenous centrifuge facility at the Lanzhou plant as a demonstration facility; this facility was commissioned in 2010 and has an estimated capacity of 0.5 million SWU/year. Another domestically produced centrifuge facility, a commercial facility with an estimated capacity of 0.5 million SWU/year, was commissioned in Lanzhou in 2012.

CNNC claims that China has completely mastered centrifuge technology and been successful in its commercialization. CNNC experts further state that China has the capacity to build 1 million SWU/year of centrifuges annually. According to these experts, new enrichment production lines are coming online each year between 2010 and 2020, and new lines will also be under construction each year.

Recent Developments: Since 2010, CNNC has expanded significantly its indigenous centrifuge enrichment capacity at several sites, including a facility at the Hanzhong plant with an estimated capacity of 1.2 million SWU/year, in operation since 2014, a facility at Plant 814 at Emeishan with an estimated capacity of around 0.8 million SWU/year, in operation around 2013, a facility at the Lanzhou plant with an estimated capacity of 1.2 million SWU/year which is set to be operational around the end of 2015. A facility at Plant 814 at

Emeishan with an estimated capacity of around 0.8 million SWU/year is under construction. Much more centrifuge enrichment capacity has been actively planned to meet the “self-sufficiency” requirement set by the government for the country’s ambitious nuclear power development plans.

Besides the facilities at Lanzhou, Hanzhong, and Emeishan, the CNNC also reportedly plans to build a larger uranium processing complex with an enrichment capacity of around 7 million SWU/year. China could easily have a total estimated enrichment capacity of 12 million SWU/year by 2020, which is about one-third more than domestic industry is expected to require.

CNNC experts emphasize that the company is following the policy of “meeting its domestic demand and targeting the international markets” in supply of enrichment services. China has been pursuing a fully independent enrichment capability, which includes R&D, engineering, manufacturing, and operations.

China’s Rapidly Expanding Indigenous Centrifuge Enrichment Capacity

Lanzhou Uranium Enrichment Plant: This plant has centrifuge facilities organized into four projects. The first centrifuge project (reported capacity of 0.5 million SWU/year), called Lanzhou Centrifuge Project 1 and also referred to as the Russian-supplied Phase III, has operated since 2001. Since 2007, the Lanzhou plant has built three additional indigenous centrifuge projects.

- In June 2007, CNNC formally initiated Lanzhou Centrifuge Project 2 (officially, Lanzhou Centrifuge Commercial Demonstration Project) as an indigenous demonstration facility. This facility was commissioned in 2010 and has an estimated enrichment capacity of about 0.5 million SWU/year.
- Lanzhou Centrifuge Project 3, a commercial centrifuge facility, was initiated in early 2010. It was commissioned in December 2012 and CNNC announced in June 2013 that it had successfully produced its first batch of enriched uranium using its own centrifuges. This commercial facility has an estimated capacity of around 0.5 million SWU/year.

- In January 2013, CNNC began construction of Lanzhou Centrifuge Project 4. This larger commercial centrifuge facility will have an estimated capacity of 1.2 million SWU/year. The main processing buildings were half finished by early 2015. It is expected to be complete by the end of 2015.

Hanzhong Enrichment Plant: This plant has four centrifuge facilities, including three Russian-supplied centrifuge facilities built under Phases I, II, and IV of the bilateral agreements, and a much larger indigenous centrifuge facility referred to officially as the North Expansion Centrifuge Project (Hanzhong 4).

After the Lanzhou demonstration centrifuge project was commissioned successfully in 2010, Hanzhong started to construct its own indigenous centrifuge project in 2012. This project was completed in 2013 and began operations around 2014. It is estimated to have a total capacity of about 1.2 million SWU/year.

Uranium Enrichment Facilities of Plant 814: CNNC also produces enriched uranium products for both military and civilian purposes at Plant 814 in Sichuan province. Plant 814 includes an enrichment plant in the Jinkouhe district of Leshan city (often referred to as the Heping GDP) and a larger commercial centrifuge plant at Shuangfu of Emeishan city.

After it ended HEU production for weapons in 1987, the Heping GDP likely operated for non-weapons military or dual uses.

To meet increasing SWU demand for the development of China's nuclear power industry, Plant 814 built a larger commercial centrifuge facility (Emeishan centrifuge project 1) near Emeishan city around 2010-2011. This facility probably began operating around 2013. This Emeishan facility has an estimated capacity of around 0.8 million SWU/year. Moreover, another CEP project (Emeishan centrifuge project 2) seems at an early construction stage at the site, which has an estimated capacity of around 0.8 million SWU/year as well. This facility could be commissioned around 2016.

Meeting China's Commercial Demand for Enriched Uranium

Based on China's official plan for nuclear power development, we can estimate that annual SWU requirements will increase to about 9 million SWU in 2020 from about 3 million SWU in 2014, and the cumulative SWU requirement through 2020 will be about 44 million SWU.

Based on current practice and CNNC's plans for centrifuge enrichment capacity, China should face no challenge in supplying a total capacity of about 12 million SWU/year by 2020. If these estimates are correct, cumulative domestic supply of enriched uranium would total about 58 million SWU over the same period between 2014 and 2020. This suggests that China could have a supply of enrichment capacity over 30 percent greater than its cumulative requirements through 2020.

In addition, when China purchases foreign reactors, it often requires the foreign vendors to supply the first few loads of enriched fuel. Such existing deals could further save China around 14 million SWU during the period between 2014 and 2020. One major justification for importing enriched uranium has been to conserve the country's own uranium resources.

Based on information presented in this report, China could have a total surplus of around 28 million SWU through 2020, which could be sold on the international market. This would be consistent with CNNC's policy of "meeting its domestic demand and targeting the international markets" in supply of enrichment services.

In light of the above discussion, China should address international concerns about the proliferation implications of the development of centrifuge technology. China has issued several relevant regulations controlling nuclear exports, and the government should take measures to assure effective implementation and enforcement of regulations and policies.

| Table ES-1: China's Uranium Enrichment Facilities Project | | |
|--|--|--|
| Facility | Capacity* (million SWU/year) | Comments |
| Lanzhou GDP | 0.2 (pre-1979), 0.3 (post-1979) | Operation in 1964; stopped HEU production in 1979; Closed in 2000. |
| Lanzhou CEP 1 (Russia-supplied phase III) | 0.5 | Operation in July 2001. Russian 6 th Gen. Centrifuges. |
| Lanzhou CEP 2 (demonstration project, domestic) | 0.5 | On July 4, 2008 started construction; operation in July 2010. |
| Lanzhou CEP 3 (domestic) | 0.5 | Construction almost finished in 2010. Commission in December 2012. |
| Lanzhou CEP 4 (domestic) | 1.2 | Started construction in 2013. By March 2015, half of building was completed. |
| Hanzhong CEP 1 (Russian-supplied phase I) | 0.2 | Operation in February 1997. Russian 6 th Gen. Centrifuges. IAEA Safeguards. |
| Hanzhong CEP 2 (Russian-supplied phase II) | 0.3 | Operation in January 1999. Russian 6 th Gen. Centrifuges. IAEA Safeguards. |
| Hanzhong CEP 3 (Russian-supplied phase IV) | 0.5 | Construction started in 2009 and conducted trials in 2011. Normal operation in 2013. Russian 7 th & 8 th Gen. Centrifuges. |
| Hanzhong CEP 4 (North Expansion Centrifuge Project, domestic) | 1.2 | Construction permit on January 4, 2012. Trials in 2013. Normal operation in 2014. |
| Heping GDP 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 | Civilian purpose. Project initiated in 2008. Started construction around 2010–2011. Operation around 2013. |
| Emeishan CEP 2 of plant 814? | (0.8) | Earlier construction stage in 2014, still building in early 2015. Could be operational around 2016? |

** Based on author's estimates, published sources, and interviews with Chinese nuclear experts and officials.*

INTRODUCTION

China leads the world in the pace of nuclear development and in new reactor construction. By May 2015, China had 27 power reactors (with capacity of 24 gigawatts-electric (GWe)) in operation with 24 units under construction.¹ In October 2012, after comprehensive post-Fukushima safety inspections of all plants in operation and under construction, China's State Council issued a new "Medium- and Long-Term Nuclear Power Development Plan (2011–2020)."² China expects its total nuclear capacity to be 58 GWe with another 30 GWe under construction by 2020,³ and much more is under consideration for the coming decades.

In 2004, China's policy on the development of nuclear power was changed from endorsing "moderate development" to "active development." To meet the expected rapid increase in uranium requirements, uranium exploration in China accelerated greatly, both in terms of expenditures incurred and meters drilled. Consequently, China's identified uranium resources increased to 265,500 metric tons of uranium (tU) in 2012 from 85,000 tU in 2004—an over three-fold increase.⁴ China has more than 2 million tU of potential resources.⁵

Meanwhile, the central government has adopted a strategy that combines domestic production, overseas exploitation, and purchases on the world marketplace in uranium. Known as the "Three One-Thirds" rule, this strategy mandates that one-third of China's uranium supplies come from domestic supply, one-third from direct international trade,

1 International Atomic Energy Agency (IAEA), "Power Reactor Information System: China, People's Republic Of," IAEA website, last modified April 26, 2015, <http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=CN> (accessed May 29, 2015).

2 Government News, "Wen Jiabao Chairs Executive Meeting of the State Council," (in Chinese) website of the Central People's Government of the People's Republic of China, October 24, 2012, http://www.gov.cn/jdhd/2012-10/24/content_2250357.htm (accessed April 27, 2015).

3 Information Office of the State Council, *China's Energy Policy 2012* (in Chinese) (Beijing, China: October 24, 2012), http://news.xinhuanet.com/english/china/2012-10/24/c_131927649.htm (accessed April 27, 2015).

4 Based on Red Book series from 2005 to 2014: OECD-NEA and IAEA, *Uranium [various years]: Resources, Production and Demand*, OECD, International Atomic Energy Agency, 2005–2014.

5 See, e.g., China Academy of Engineering, *China's Medium- and Long-Term Energy Development Strategy (2030, 2050)* (Beijing, China: Science Press, 2011); Li Ziyang, "Uranium Resource Potential and Recent Major Exploration Progress in China," presentation to the China International Nuclear Symposium, Beijing, China. November 7–9, 2012, http://proceedings.world-nuclear.org/CINS3/presentations/23_Uranium_resource_potential_and_recent_major_exploration_progress_in_China.pdf. The difference between identified and potential resources should be noted. An identified (or known) uranium resource has a fairly accurately determined grade and tonnage. In contrast, uranium potential is a looser term indicating what is roughly expected based on knowledge of previously discovered deposits and region-wide geological mapping. To cross the line from potential to known uranium reserves requires significant amounts of exploration work.

and another third from overseas mining by Chinese firms. Consequently, China has recently secured a huge amount of overseas uranium resources—about three times the size of its own identified uranium reserves. More could easily be added, which would make for more than enough to meet the requirements of the most ambitious version of the country’s nuclear energy plan through 2050.⁶

While China has secured the supply of natural uranium (through domestic and overseas resources) for its nuclear power development for several coming decades, there remains the question of how this uranium will be enriched. The China National Nuclear Corporation (CNNC)—the entity solely responsible for enrichment services in China⁷—has said it maintains a policy of “self-sufficiency” in the supply of enrichment services.⁸ As this report will describe, in 2014, China needed about 3 million SWU (separative work units) of enrichment to fuel its operational nuclear power plants. In 2020, demand is expected to be about 9 million SWU (see figure 11).

Many Western sources estimate that China’s current SWU capacity will not be able to meet currently projected demand. For instance, the World Nuclear Association (WNA) estimated that China would have a total enrichment capacity of 2.2 million SWU/year in 2014, including 1.5 million SWU from Russian-supplied centrifuges and 0.7 million SWU/year from indigenous facilities; and projected a total of 3 million SWU/year by 2015.⁹ However, as this paper will describe, 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 about 2 million SWU/year is under construction, and may have the ability to add

6 Hui Zhang and Yunsheng Bai, “China’s Access to Uranium Resources,” (Cambridge, MA: Project on Managing the Atom, Harvard Kennedy School, May 2015), <http://belfercenter.ksg.harvard.edu/files/chinasaccesssouraniumresources.pdf>.

7 CNNC’s control of enrichment could change as the China General Nuclear Power Corporation (CGN) plans to evolve into such services both domestically and abroad. CGN plans to have a deal with the CNNC to establish a joint-venture for a new nuclear fuel complex including enrichment. For details see Phil Chaffee, “Fuel Cycle: CNNC-CGN Guangdong Fuel Plant Rises From the Ashes,” *Nuclear Intelligence Weekly*, Vol. IX, No. 17 April 24, 2015, pp. 4-5). Also, CGN made a deal in December 2014 for a joint CGN-Kazatomprom fuel fabrication plant in Kazakhstan. This deal could lead CGN to import fuel assemblies in which commercial SWU purchased elsewhere enters the Chinese market See Phil Chaffee and Kevin Pang, “Washington Spot Price Weakens Again While Producers Shrug,” *Nuclear Intelligence Weekly*, Vol. IX, No. 17 April 24, 2015, p.2). These CGN plans would break CNNC’s dominance on domestic enrichment services.

8 Li Guanxing, “Status and Future of the Front-end of Completely Independent Uranium Enrichment,” *China Nuclear Power* (in Chinese), Vol. 3, No. 1 (2010).

9 World Nuclear Association (WNA), “Uranium Enrichment (Updated April 2015),” WNA website, n.d., <http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/> (accessed June 25, 2015).

1 million SWU/year of additional capacity annually. These estimates are much larger than previous public estimates of China's total enrichment capacity.¹⁰

The purpose of this report is to provide a better understanding of China's uranium enrichment capacity based on satellite imagery and other publically available information, to discuss the development of China's uranium enrichment industry, and to examine whether China's enrichment capacity can meet commercial SWU requirements for power reactors for the coming decade and beyond.

Section I reviews the development of China's uranium enrichment industry. In Section II, I discuss the status of Lanzhou uranium enrichment plant and estimate its enrichment capacity. Section III discusses the status of Hanzhong uranium enrichment plant and estimates its enrichment capacity. In Section IV, I discuss the status of Plant 814 at Emeishan city and estimate its enrichment capacity. Section V examines whether China's total enrichment capacity can meet commercial SWU requirements. Finally, Section VII offers some concluding comments and recommendations.

10 See, e.g., WNA: "Uranium Enrichment"; Phil Chaffee and Kim Feng Wong, "China's Indigenous Capacity may be Double Previous Estimates," *Nuclear Intelligence Weekly*, March 1, 2013, pp. 3-4; and Jeffrey Lewis, "China's New Centrifuge Plants," *Arms Control Wonk*, September 17, 2013, <http://lewis.armscontrolwonk.com/archive/6826/chinas-new-centrifuge-plants>[access date]. These previous estimates did not account for new centrifuge facilities at Emeishan, and underestimated enrichment capacities of the domestic CEPs at Hanzhong and Lanzhou plants. For instance, more recent information suggests that the Hanzhong CEP 4 has a capacity about 1.2 million SWU/year (instead of the previously assumed 0.25 million SWU/year).

I: MAJOR DEVELOPMENTS IN CHINA'S URANIUM ENRICHMENT CAPACITY

China currently operates three enrichment plants: the Lanzhou uranium enrichment plant (Plant 504) in Gansu province, Hanzhong uranium enrichment plant (Plant 405) in Shaanxi province, and Plant 814 in Sichuan province, which has facilities at Jinkouhe and Emeishan.¹¹

The Military Origins of Chinese Enrichment

China's uranium enrichment industry was initiated in the late 1950s to produce highly enriched uranium (HEU) for its nuclear weapon program.¹² China is believed to have ended HEU production for weapons in 1987.¹³ China produced HEU for weapons at two facilities: the Lanzhou gaseous diffusion plant (GDP) and Heping GDP (the Jinkouhe facility of Plant 814).¹⁴ 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 1979.¹⁵ Since 1980, it shifted to making LEU for civilian power reactors, and it was shut down in December 2000 and replaced by a centrifuge enrichment plant (CEP) after 2001.¹⁶ The Heping plant produced HEU for weapons from 1970 to 1987.¹⁷ Since 1987, the plant is

11 The Jinkouhe plant is often called Heping uranium enrichment plant in western media, and is located in Heping Yuzu township, near the Jinkouhe district of Leshan city. Lately, Plant 814 has also operated centrifuge facilities near Emeishan city. In this paper, "Heping facility" refers to the Plant 814 facility in Jinkouhe, and "Emeishan facility" to the Plant 814 facility in Emeishan city.

12 Li Jue, Lei Rongtian, Li Yi, and Li Yingxiang, eds., *China Today: Nuclear Industry* (in Chinese) (Beijing, China: China Social Science Press, 1987).

13 Hui Zhang, "Chapter 7: China," in International Panel on Fissile Materials, *Global Fissile Material Report 2010: Balancing the Books: Production and Stocks* (Princeton, NJ: Princeton University, 2011). <http://belfercenter.ksg.harvard.edu/files/Hui-Zhang-China-Chapter-Global-Fissile-Materials-Report.pdf>.

14 Zhang, "Chapter 7: China."

15 Zhang, "Chapter 7: China."

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

17 Previous estimates assumed the plant started operation in 1975. Based on new Chinese information, it began operating on June 25, 1970 (see, e.g., Wang Zhaofu, "60 Years of New China's Nuclear Energy Development Key Events," *China Nuclear Energy* (in Chinese), No.5 (2009). Also available at: <http://www.china-nea.cn/html/2009-11/4239.html>). Regarding HEU production for weapons, see details in: Hui Zhang, "Chapter 7: China."

reported to have continued operations.¹⁸ It is assumed to be operating for non-weapons military or dual uses, including producing LEU for naval reactors, and HEU for tritium production reactors and research reactors.

The Emergence of Civilian Enrichment in China

As China deepened its “shift from military to civilian” in the nuclear industry during the late 1980s, CNNC was to adopt less-costly centrifuge enrichment technology to replace its gaseous diffusion plants. To supply enrichment services for its power reactors—during the 1991–1994 period, China planned to operate three PWRs with a total capacity of 2.3 GWe—China would need about 0.3 million SWU/year. However, development of the country’s own centrifuges for commercial use was slow. China decided to follow the same technology development strategy it had pursued for acquiring advanced power reactor technology: importing foreign technology and then localizing it.

In 1993, China and Russia signed an agreement to build Russian-supplied centrifuge facilities at the Hanzhong plant, in two phases. The first phase had a capacity of 0.2 million SWU/year and began operations in February 1997. The second phase had a capacity of 0.3 million SWU/year and was commissioned in January 1999.¹⁹ In 1995, China decided to build an additional eight reactors (with a total capacity of 6.9 GWe) over the 1996–2002 period, including two domestic PWRs and two reactors to be purchased from each of France (PWRs), Canada (heavy water reactors (HWRs)) and Russia (water-water power reactors [VVERs]). Thus, China planned to operate nine PWRs with a total capacity of 7.7 GWe by the early 2000s, which would require an enrichment capacity of about 1 million SWU/year. Consequently, in 1996 China and Russia agreed to build another centrifuge facility at Lanzhou enrichment plant with a capacity of 0.5 million SWU/year, as the third phase in the acquisition of Russian-supplied centrifuge facilities. This Phase III facility was commissioned in July 2001. It is reported that the Russian-supplied centrifuges are based on the sixth generation of Russian designs.²⁰ Together, the three phases and their 1 million SWU/year of capacity could meet the requirements of China’s nuclear power development plans in the 1990s. In addition, when China purchases foreign reactors, it also often requires foreign vendors to supply the first few loads of reactor fuel. These deals further

18 See, e.g., Cheng Lili, “Plant 814: The New Era of ‘Small Yan’an,’” *Workers’ Daily* (in Chinese), March 26, 2010. (Note: Yan’an in Shannxi province is famous as a major site in the history of the establishment of the P.R. China in 1949.)

19 Wang, “60 Years of New China’s Nuclear Energy Development Key Events.”

20 WNA, “China’s Nuclear Fuel Cycle (Updated April 2015),” WNA website, n.d., <http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/> (accessed June 25, 2015).

save China both natural uranium and SWU (as discussed in the following section). However, SWU saved in these deals account for only a small percentage of China's domestically produced SWU. Also, it has been reported that China has occasionally exported SWU to other states, including through sales of LEU to India in the 1990s.²¹

After China adopted in the mid-2000s a policy of "active development" of nuclear power, it reached with Russia in May 2008 an agreement on the construction of another centrifuge facility with a capacity of 0.5 million SWU/year at Hanzhong plant as the fourth and final phase; this facility was commissioned in July 2011. Altogether, the four phases of Russian-supplied centrifuge facilities account for a reported total of 1.5 million SWU/year.²²

The Indigenization of Chinese Centrifuges

In October 1969, China decided to build plant 405 as a "Third Line" facility and worked on uranium enrichment technologies. China had conducted R&D on centrifuge technology since 1958, and started to emphasize centrifuge work in the mid-1970s.²³ The major players include CNNC Research Institute of Physical and Chemical Engineering of Nuclear Industry at Tianjing and Plant 405.²⁴ Other academic units, including Tsinghua University, were actively involved as well.²⁵ China had intensified its centrifuge R&D efforts since the late 1970s and early 1980s.²⁶ In the mid-1980s, Plant 405 constructed and operated a pilot centrifuge facility under project 405-1 which apparently was equipped with supercritical centrifuges.²⁷ It is reported AQ Khan gave URENCO centrifuge technology to China and helped build a centrifuge plant at Hanzhong around early 1980s.²⁸ However, it is not clear whether AQ Khan made significant contribution to the project

21 Express News Service, "Russia first off the NSG block, says it will supply fuel to Tarapur," *The Indian Express* (website), March 14, 2006, <http://archive.indianexpress.com/news/russia-first-off-the-nsg-block-says-it-will-supply-fuel-to-tarapur/463/0>.

22 WNA, "China's Nuclear Fuel Cycle."

23 Li Jue, Lei Rongtian, Li Yi and Li Yingxiang, eds., *China Today: Nuclear Industry* (Beijing: China Social Science Press, 1987) (In Chinese).

24 Communications with CNNC nuclear experts, October 2014.

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

26 Communications with CNNC nuclear experts, October 2014.

27 See, e.g., Huang Wenhui and Qian Xikang, "Persons of Tsinghua University in Qinbashan," *China Youth Science and Technology* (in Chinese), No.12, (2003). <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, see <http://www.newsmth.net/nForum/#!article/TsinghuaCent/353223>.

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

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 early 1990s to import a Russian centrifuge facility to replace the project 405-1 as project 405-1A.²⁹

As Russian centrifuge facilities were imported, CNNC started localization of the imported technology and designed its own centrifuges. CNNC’s Research Institute of Physical and Chemical Engineering of Nuclear Industry at Tianjing is the major player in the development and design of centrifuges. It produced its first centrifuge in 2002 and then began the industrialization of centrifuge technology for production.³⁰ The process was accelerated in accordance with China’s adoption of a policy of “active development” of nuclear power in 2004. In 2007, CNNC started a project to construct an indigenous centrifuge facility at the Lanzhou plant as a demonstration facility; this facility started operation on July 12, 2010³¹ and has a capacity of 0.5 million SWU/year.³² Another domestically produced centrifuge facility, a commercial facility with an assumed capacity of 0.5 million SWU/year (see details in Section II), was commissioned there in December 2012³³ and successfully produced LEU products from June 2013. Thus, CNNC can claim that China has completely mastered centrifuge technology and been successful in its commercialization.³⁴

29 Communications with CNNC nuclear experts, October 2014.

30 “Lei Zengguang: China has Realized its Uranium Enrichment Autonomy,” interview (in Chinese) China Atomic Energy Authority website, May 17, 2013, <http://www.caea.gov.cn/n16/n1223/542004.html> (accessed June 25, 2015).

31 CNNC, “1995 to 2000” in “60 Events in 60 Years,” <http://www.cnncc.com.cn/publish/portal0/tab904/info88022.htm>; also, China’s National Nuclear Safety Administration (NNSA), “Annual Report 2010,” (in Chinese), <http://haq.mep.gov.cn/haqkw/201402/P020140217369108759122.pdf>.

32 Sam Trantum, “China’s Indigenous Centrifuge Enrichment Plant,” *Nuclear Intelligence Weekly*, October 25, 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. This capacity is consistent with estimates offered in communications with Chinese nuclear experts in July, 2013.

33 CNNC, “1995 to 2000”; NNSA, “Annual report 2012,” (in Chinese), <http://haq.mep.gov.cn/haqkw/201402/P020140217370292464656.pdf>.

34 Yu Siluan, “A Completely Independent Uranium Enrichment Technology: Industrialization Achieved and Development of a New Generation of Centrifuges,” *People’s Daily* (in Chinese), June 22, 2013, http://paper.people.com.cn/rmrb/html/2013-06/22/nw.D110000renmrb_20130622_6-01.htm.

Recent Developments

CNNC experts state that China has the capacity to build 1 million SWU/year of centrifuges annually.³⁵ According to these experts, new enrichment production lines will be coming online each year between 2010 and 2020, and new lines will also be under construction each year.³⁶

Indeed, recent satellite imagery and interviews suggest (see below) that since 2010, CNNC has expanded significantly its indigenous centrifuge enrichment capacity at several sites, including a facility at the Hanzhong plant with an estimated capacity of 1.2 million SWU/year, in operation since 2014, a facility at Plant 814 at Shuangfu of Emeishan with an estimated capacity of around 0.8 million SWU/year, in operation since around 2013, a facility at the Lanzhou plant with an estimated capacity of 1.2 million SWU/year which is set to be operational around the end of 2015, and a facility at the Shuangfu of Emeishan with an estimated capacity of around 0.8 million SWU/year which seems at an early construction stage and could be operational in 2016. Much more centrifuge enrichment capacity has been actively planned to meet the “self-sufficiency” requirement set by the government for the country’s ambitious nuclear power development plans. The head of the Lanzhou plant said in June 2013 that these centrifuge machines (presumably both operational and planned) were capable of meeting not only the existing requirement but also the entirety of projected demand through 2020.³⁷

Besides the facilities at Lanzhou, Hanzhong, and Emeishan, until June 2013 CNNC had a plan (formulated in February 2012) to build a large-scale uranium processing complex in Heshan city in Guangdong province. The Heshan project would have been a CNY 40 billion Yuan (USD 6 billion) uranium processing complex for uranium purification and conversion, uranium enrichment, and fuel fabrication. It was reported that the plant’s nuclear fuel products would meet half the demand of China’s nuclear power industry in 2020,³⁸ which would mean the enrichment capacity could have totaled 5 million SWU/year (see Section V for details). One lead of CGN pointed out the capacity was 7 million

35 Kang Rongyuan and Gong Yufeng, “Suggestions on China’s Nuclear Fuel Development and Strategy,” (in Chinese) Chinese Nuclear Energy Association website, February 4, 2013, www.china-nea.cn/html/2013-02/25688.html (accessed June 25, 2015).

36 Li, “Status and Future of the Front-end of China’s Nuclear Fuel Cycle.”

37 Zhang Xiaobo, “China Develops Own Tech to Enrich Uranium,” *Global Times* (online), June 25, 2013, <http://www.global-times.cn/content/791301.shtml#.UclTyj7k5YQ>.

38 Liu Qingshan, “Waiting to Know the East Wind: Heshan Setback,” *China SOE*, No. 4, (2014), pp. 28–29. Based on an interview with CNNC president Sun Qin. The China SOE (State Owned Enterprise) is run by the State Own Assets Supervision and Administration Commission of the State Council.

SWU/year.³⁹ However, the Heshan project was cancelled in July 2013 after large-scale protests against the project.⁴⁰ The protestors voiced concerns about public health impacts and environmental costs. They complained that the project lacked an adequate environmental impact assessment and that the ten-day public consultation on social stability impacts was too short. However, CNNC has faced no challenges in choosing a new site for the project given that several local governments, believing that the project will promote economic development, are currently competing to host it.⁴¹ Indeed, CNNC and CGN have an active plan to continue establishing the nuclear fuel complex.⁴² In addition, the Lanzhou and Emeishan plants still have physical space for construction and plans exist to expand their enrichment capacities. It has generally taken about two years from the beginning of construction to the commissioning of a centrifuge enrichment facility with a capacity of around 1 million SWU/year, including one year for the building of enrichment halls and the installation of centrifuges, and one year for trial tests, adjustments to the facility, and review and approval by China National Nuclear Safety Administration (NNSA).⁴³ Considering CNNC's current estimated operational capacity of 4.5 million SWU/year, around 2 million SWU/year under construction at Lanzhou and Emeishan sites (as discussed in following sections), and assuming an added million SWU/year of additional capacity each year, China could easily have a total enrichment capacity of 12 million SWU/year by 2020, which is more than domestic industry will demand—about 9 million SWU/year by 2020 (see details in Section V).

The CNNC experts emphasize that the company is following its policy of “meeting its domestic demand and targeting the international markets” in supply of enrichment services.⁴⁴ China has been pursuing a fully independent enrichment capability, which includes R&D, engineering, manufacturing, and operations. Those experts further state that the efficiency of indigenous centrifuges is much higher than the efficiency of those imported for the first three phases constructed under the China-Russia agreements.⁴⁵ CNNC is also developing a new generation of more advanced and economic centrifuges, and has made significant progress with the key technological challenges.⁴⁶

39 WNA, “China’s Nuclear Fuel Cycle.”

40 Liu, “Waiting to Know the East Wind: Heshan setback.”

41 Communications with Chinese nuclear experts, October, 2014.

42 See Phil Chaffee, “Fuel Cycle: CNNC-CGN Guangdong Fuel Plant Rises From the Ashes.”

43 Communications with Chinese nuclear experts, October, 2014.

44 Li, “Status and Future of the Front-end of China’s Nuclear Fuel Cycle.”

45 Communication with CNNC nuclear experts, July, 2013.

46 Liu Yin, “China has Accomplished Complete Independence in Uranium Enrichment Technology,” *Science and Technology Daily* (in Chinese), June 24, 2013, http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/html/2013-06/24/content_209817.htm.

II: LANZHOU URANIUM ENRICHMENT PLANT

Lanzhou enrichment plant (the official Chinese name of which is CNNC Lanzhou Uranium Enrichment Co., Ltd, or Plant 504) hosts a gaseous diffusion facility and centrifuge facilities organized into four projects (see figure 1).

The GDP was shut down on December 31, 2000. During 2001 and 2002, the facility finished cleaning up radioactivity in preparation for decommissioning. Since then, the GDP facility has been “sealed and [under] maintenance.”⁴⁷ The first centrifuge project at the Lanzhou plant (reported capacity of 0.5 million SWU/year), called Lanzhou Centrifuge Project 1 and also referred to as Russian-supplied Phase III, has operated since July 10, 2001.⁴⁸ Since 2007, the Lanzhou plant has built three additional indigenous centrifuge projects as discussed in detail in the following (see table 1).

China’s indigenous centrifuges are most likely based on Russian technology. The Russian-supplied centrifuges were sixth-generation units.⁴⁹ Russia’s centrifuges have been subcritical through the eighth generation.⁵⁰ The Russian centrifuge is relatively small, and usually has a total length, including the top and bottom bearing when assembled, 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.⁵¹ The separative capacity of each sixth-generation centrifuge is about 2.5 SWU/year.⁵² Russia’s practice is to assemble these short subcritical centrifuges into stacks generally three to four, but up to seven, shelves high). Each level in a module has 20 machines (two rows of ten) (see figure 2).⁵³

47 Jing et al., “Economic Analysis of Decommissioning of Lanzhou Gaseous Diffusion System.”

48 Wang, “60 Years of New China’s Nuclear Energy Development Key Events.”

49 WNA, “China’s Nuclear Fuel Cycle.

50 Centrifuges are either ‘subcritical’ or ‘supercritical.’ David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford: Oxford University Press, 1997), p. xviii, includes a standard definition: 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).

51 Albright et al, *Plutonium and Highly Enriched Uranium 1996*, p. 106.

52 Albright et al, *Plutonium and Highly Enriched Uranium 1996*, p.106.

53 Oleg Bukharin, “Russia’s Gaseous Centrifuge Technology and Uranium Enrichment Complex,” Working Paper of the Program on Science and Global Security, Woodrow Wilson School of Public and International Affairs Princeton University, January 2004, <http://www.partnershipforglobalsecurity-archive.org/Documents/bukharinrussianenrichmentcomplexjan2004.pdf>.

In June 2007, CNNC formally initiated Lanzhou Centrifuge Project 2 (officially, Lanzhou Centrifuge Commercial Demonstration Project) as an indigenous demonstration facility (see figure 3). On July 4, 2008, NNSA issued a construction permit for the project.⁵⁴ The project was contracted out to CNNC Xinneng Nuclear Engineering Co., Ltd., which became responsible for the entire construction of the CNNC centrifuge facility, including engineering design, construction, procurement, installation, and facility adjustment.⁵⁵ This demonstration facility was commissioned in December 2010.⁵⁶ Its enrichment capacity is estimated to be about 0.5 million SWU/year.⁵⁷

Figure 1: **Lanzhou Uranium Enrichment Plant**



Note: Satellite image from January 18, 2015 (Coordinates: 36°08'53.30" N/103°31'24.49" E).
Source: DigitalGlobe

54 NNSA, "Annual Report 2008," (in Chinese), http://haqkw.mep.gov.cn/haqkw/200911/t20091113_181615.htm.

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

56 CNNC, "1995 to 2000"; NNSA, "Annual Report 2010."

57 See Trantum, "China's Indigenous Centrifuge Enrichment Plant," As noted above (see footnote 32), the reported capacity is consistent with estimates offered in communications with Chinese nuclear experts in July 2013.

Figure 2: **Ural Electromagnetic Integrated Plant, Novouralsk, Russia**

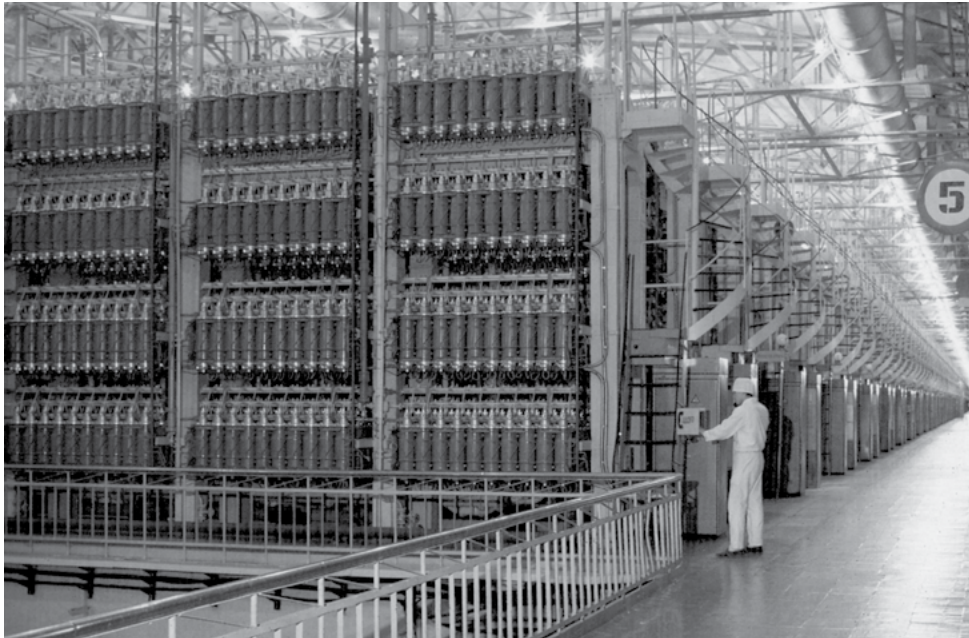


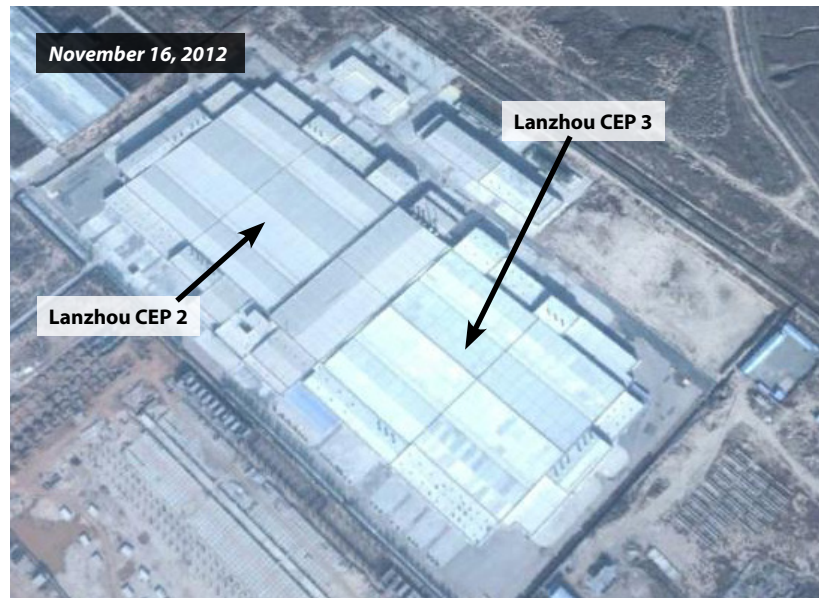
Photo credit: U.S. Dept. of Energy

Figure 3: **Lanzhou CEP 2 and CEP 3**



Note: Satellite imagery from October 3, 2010. The image shows CEP 2 was completed, CEP 3 was not.
Source: DigitalGlobe and Google Earth

Figure 4: **Lanzhou CEP 2 and CEP 3**



*Note: Satellite imagery from November 16, 2012. The image shows CEP 3 was completed.
Source: DigitalGlobe and Google Earth*

Figure 5: **Lanzhou CEP 4**



*Note: Satellite image from January 18, 2015. The image shows the enrichment building was half-completed. The pads for stack installation were under construction.
Source: DigitalGlobe*

Lanzhou Centrifuge Project 3 (a commercial centrifuge facility) was initiated in early 2010. Satellite imagery taken on October 3, 2010, (see figure 3) shows the main processing building was completed, while other parts were not finished. In satellite imagery from November 16, 2012, the facility appears to be completed (see figure 4). In 2012, the NNSA annual report stated that the company had conducted trial tests.⁵⁸ The facility was commissioned in December 2012,⁵⁹ and in June 2013 CNNC announced that it successfully produced the first batch of enriched uranium using its own centrifuges.⁶⁰ This commercial facility has an estimated capacity of around 0.5 million SWU/year.⁶¹

On January 8, 2013, NNSA issued the construction permit for Lanzhou Centrifuge Project 4.⁶² This larger commercial centrifuge facility will have an estimated capacity of 1.2 million SWU/year.⁶³ As shown in satellite imagery, the main processing buildings were half completed by early 2015 (see figure 5). It is expected to be complete and commissioned by the end of 2015. China plans to build a larger centrifuge facility with similar capacity as a next project (Lanzhou Centrifuge Project 5), and a few additional projects could follow.⁶⁴

58 NNSA, "Annual Report 2012."

59 CNNC, "1995 to 2000"; NNSA, "Annual report 2012".

60 Zhang Xiaobo, "China Develops Own Tech to Enrich Uranium"; NNSA, "Annual Report 2013," (in Chinese), <http://haq.mep.gov.cn/haqkw/201412/P020141218553855071258.pdf>.

61 Assuming this facility has the same capacity as that of the demonstration project, given that they have the same total roof footage. This estimate is consistent with estimates offered in communications with Chinese nuclear experts in July 2014.

62 NNSA, "Annual Report 2013."

63 The total footage of the enrichment building is about 2.3 times that of Lanzhou CEP 3, which has a capacity of 0.5 million SWU/year. This estimate is also consistent with estimates offered in communications with Chinese nuclear experts in February 2015.

64 Communications with Chinese nuclear experts, February 2015.

| Table 1: Lanzhou Centrifuge Facilities | | |
|---|--------------------------------|--|
| Projects | Capacity (million SWU/year) | Comments |
| Lanzhou CEP 1 (Russian-supplied Phase III) | 0.5 | Began operating in 2001. |
| Lanzhou CEP 2 (demonstration project, domestic) | 0.5 | Construction began on July 4, 2008; operating since 2010. |
| Lanzhou project 3 (domestic) | 0.5 | Construction neared completion in 2010; trial tests in 2012. Commissioned in December 2012; produced first batch of LEU products in June 2013. |
| Lanzhou project 4 (domestic) | 1.2 | Finished siting environmental review by NNSA on January 10, 2012; construction permits issued in 2013. By March 2015, half of the processing building completed as shown in satellite imagery. |

III: HANZHONG URANIUM ENRICHMENT PLANT

Hanzhong enrichment plant (Official Chinese name: CNNC Shaanxi Uranium Enrichment Co., Ltd., or Plant 405) has four centrifuge facilities (see figure 6), including three Russian-supplied centrifuge facilities built under Phases I, II, and IV of the China-Russian agreements, and a larger indigenous facility (see table 2).

The Hanzhong plant hosts imported Russian-supplied centrifuges facilities constructed in two phases under the 1993 China-Russia agreement. The first-phase facility has a reported capacity of 0.2 million SWU/year⁶⁵ and began operations in February 1997.⁶⁶ The second phase has a reported capacity of 0.3 million SWU/year⁶⁷ and was commissioned in January 1999.⁶⁸ A third-phase facility, with an reported capacity of 0.5 million SWU/year was built in 2001 at Lanzhou under a 1996 agreement.⁶⁹ After China adopted a policy of “active development” of nuclear power in the mid-2000s, it reached an agreement with Russia in May 2008 on the construction of another centrifuge facility with an assumed capacity of 0.5 million SWU/year at Hanzhong as the fourth and final phase. Construction of this unit began in 2009 and was completed in 2011. On November 1, 2012, NNSA accepted it for pre-feeding work and the facility began normal operations in 2013.⁷⁰

The Hanzhong plant is also operating a much larger indigenous centrifuge facility, which is referred to officially as the North Expansion Centrifuge Project (Hanzhong 4) because it is located to the north of the Russian facilities. After the Lanzhou demonstration centrifuge project (Lanzhou CEP 2) was commissioned successfully in 2010, Hanzhong started its own indigenous centrifuge project. On January 4, 2012, it received permission for construction.⁷¹ The project was completed in 2013 and began operations around 2014.⁷² Unlike the grounds of the Lanzhou plant, which still has space for more centrifuge facilities, available space at the Hanzhong plant is very limited. Hence, the indigenous facility

65 Oleg Bukharin, “Understanding Russia’s Uranium Enrichment Complex,” *Science and Global Security*, 2004, Volume 12, pp. 193-218.

66 Wang, “60 Years of New China’s Nuclear Energy Development Key Events.”

67 Oleg Bukharin, “Understanding Russia’s Uranium Enrichment Complex.”

68 Wang, “60 Years of New China’s Nuclear Energy Development Key Events.”

69 WNA, “China’s Nuclear Fuel Cycle”; Oleg Bukharin, “Understanding Russia’s Uranium Enrichment Complex.”

70 NNSA, “Annual Report 2012”; NNSA, “Annual Report 2013.”

71 NNSA, “Annual Report 2012.”

72 NNSA, “Annual Report 2014,” (in Chinese), <http://nnsa.mep.gov.cn/hannb/201505/P020150520499028621407.pdf>.

uses stacks with double the number of layers as those at Lanzhou's CEPs.⁷³ The facility has two main enrichment buildings with a total estimated capacity of about 1.2 million SWU/year.⁷⁴

Under its Voluntary Offer Safeguards agreement with the IAEA, China offered three Russian-supplied facilities, Phase I and II at the Hanzhong plant and Phase III at the Lanzhou plant, for selection for IAEA safeguards. Due to a shortage of funds, the IAEA picked only the Hanzhong facilities.⁷⁵ The two Russian-supplied centrifuge facilities of Phase I and 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).⁷⁶ The fact that China offered IAEA inspectors access to both the Hanzhong and Lanzhou plants very likely indicates they are both purely dedicated to civilian purposes.

73 Communications with Chinese nuclear experts, November 2014.

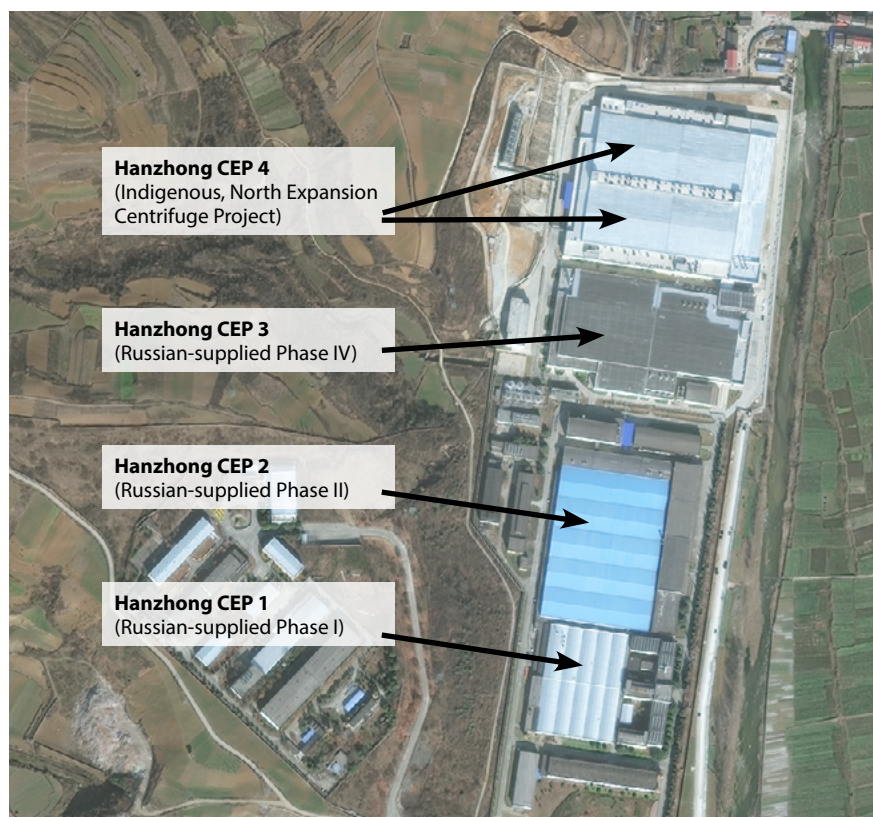
74 This is estimated based on a comparison between the total roof footage of the enrichment buildings with that of the buildings at Lanzhou CEP 2, and considering that the facility uses stacks with double the number of layers as those at Lanzhou's CEPs. Also, this estimate is consistent with communications with Chinese nuclear experts in November 2014.

75 Communications with Chinese nuclear experts, October 2014.

76 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 (Vienna: IAEA, 2001).

| Table 2: Hanzhong Centrifuge Facilities | | |
|--|--------------------------------|---|
| Projects | Capacity (million SWU/year) | Comments |
| Hanzhong CEP1 (Russian-supplied Phase I) | 0.2 | Operating since February 1997; subject to IAEA Safeguards. |
| Hanzhong CEP2 (Russian-supplied Phase II) | 0.3 | Operating since January 1999; subject to IAEA Safeguards. |
| Hanzhong CEP3 (Russian-supplied Phase IV) | 0.5 | Construction began in 2009; completed and conducted trials in 2011. NNSA conducted pre-feeding in November 2012. Operating normally since 2013. |
| Hanzhong CEP4 (North Expansion Centrifuge Project, domestic) | 1.2 | NNSA issued construction permit on January 4, 2012. Trials in 2013. Operating normally since 2014. |

Figure 6: **Hanzhong Uranium Enrichment Plant**



Note: Satellite image from January 27, 2013 (Coordinates: 33°15'47.70" N/107°25'52.74" E).
Source: DigitalGlobe.

IV: URANIUM ENRICHMENT FACILITIES OF PLANT 814

CNNC also produces enriched uranium products for both military and civilian purposes at Plant 814 in Sichuan province, which has enrichment facilities in Jinkouhe district of Leshan city (see figure 7) and Emeishan city (see figure 8). Plant 814 is often called Heping uranium enrichment plant in western media, and is located at Heping Yuzu township, near Jinkouhe district of Leshan city. Lately, Plant 814 has also operated centrifuge facilities near Emeishan city. In this paper, “Heping facility” refers to the Plant 814 facility at Jinkouhe, and “Emeishan facility” to the Plant 814 facility at Shuangfu of Emeishan city.

The Heping gaseous diffusion plant began operating on June 25, 1970 (earlier than 1975, the year assumed in previous estimates).⁷⁷ It is believed to have stopped HEU production for weapons in 1987 as a result of China’s “military-to-civilian conversion” policy.⁷⁸ Chinese publications indicate that the facility continued operations, however.⁷⁹ China still needs enriched uranium products for other non-weapons military uses, including LEU for naval reactors, and HEU for tritium production and some research reactors. These are the likely purposes for continued Plant 814 production, given that, as mentioned above, the Lanzhou and Hanzhong centrifuge plants appear to be dedicated entirely to civilian purposes. The fact that China still uses its code name to refer to Plant 814 suggests that it is more sensitive than the Lanzhou and Hanzhong plants, which both have official public names that have replaced their previous code names of Plant 504 and Plant 405, respectively. The Heping facility therefore may be military or dual use.⁸⁰ Moreover, it is reported Plant 814 accomplished a technology update and renovation around 2006.⁸¹

77 Wang, “60 Years of New China’s Nuclear Energy Development Key Events.”

78 Hui Zhang, “Chapter 7: China.”

79 See, e.g., Cheng, “Plant 814: the New Era of ‘Small Yan’an.’”

80 The Heping GDP was estimated to have a capacity of 0.23 million SWU/year before 1987 (see, e.g., Hui Zhang, “Chapter 7: China”). However, new information indicates that the output of the facility was increased by 45% around 2004 (see: Cheng, “Plant 814: the New Era of ‘Small Yan’an’”). Consequently, the Heping plant could have a capacity of between 0.3 and 0.4 million SWU/year.

81 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. If the upgrade was meant only for the Heping GDP, it may indicate its replacement by a centrifuge enrichment plant. 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 solid evidence to confirm this.

To meet the increasing SWU demand for China's nuclear power development, it appears that Plant 814 built a larger commercial centrifuge facility (Emeishan CEP 1) near Emeishan city. Based on the city's official documents, the centrifuge project (referred as Plant 814 centrifuge project 1) was planned to be started in 2008.⁸² While there is no public information of the specific location, based on a 2014 satellite image (see figure 9) it could be at the town of Shuangfu near Emeishan city. The Emeishan CEP 1 started construction around 2011. This facility may have gone into operation around 2013. The available evidence suggests that this facility could have a capacity around 0.8 million SWU/year.⁸³

Based on a satellite image taken on October 5, 2014 (see figure 9), another CEP project (Emeishan CEP 2) seems at an early construction stage at the site. Based on a satellite image (taken on February 16, 2015) on Google Earth (see figure 10), the construction made a significant progress. It generally takes about two years from construction to commissioning for a centrifuge facility. Thus, this facility could be commissioned around 2016. Given that the total footage of the enrichment building is estimated to be similar to that of the Emeishan CEP 1, Emeishan CEP 2 is assumed to have a capacity around 0.8 million SWU/year. In addition, the satellite image shows that the space alongside the CEP 1 is perhaps ready for an additional CEP.

82 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> (accessed June 25, 2015). This governmental document stated 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.

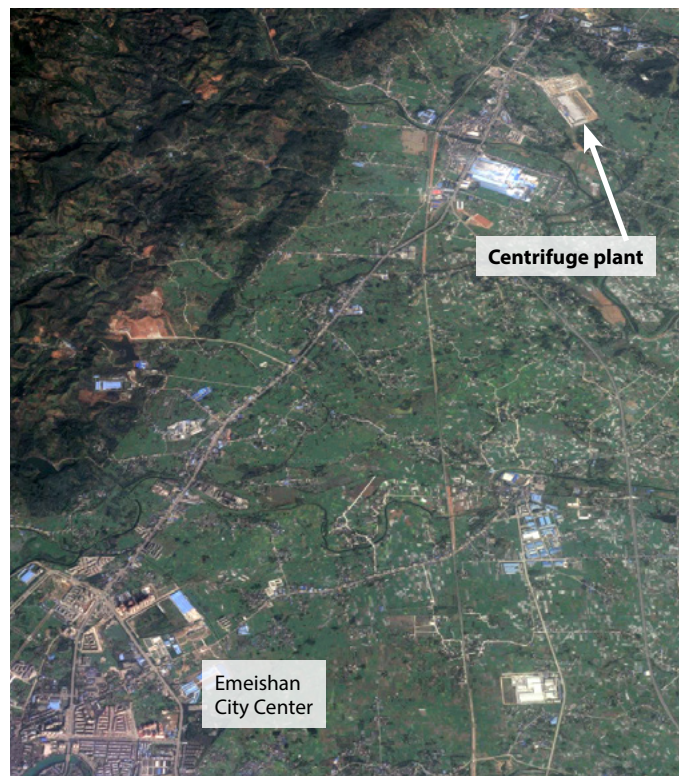
83 The total footage of the presumed enrichment building is about 1.6 times of that of Lanzhou CEP 3 which has a capacity of 0.5 million SWU/year. This estimate is also consistent with communications with Chinese nuclear experts in June 2015.

Figure 7: **Heping Uranium Enrichment Plant of Plant 814 at Jinkouhe**



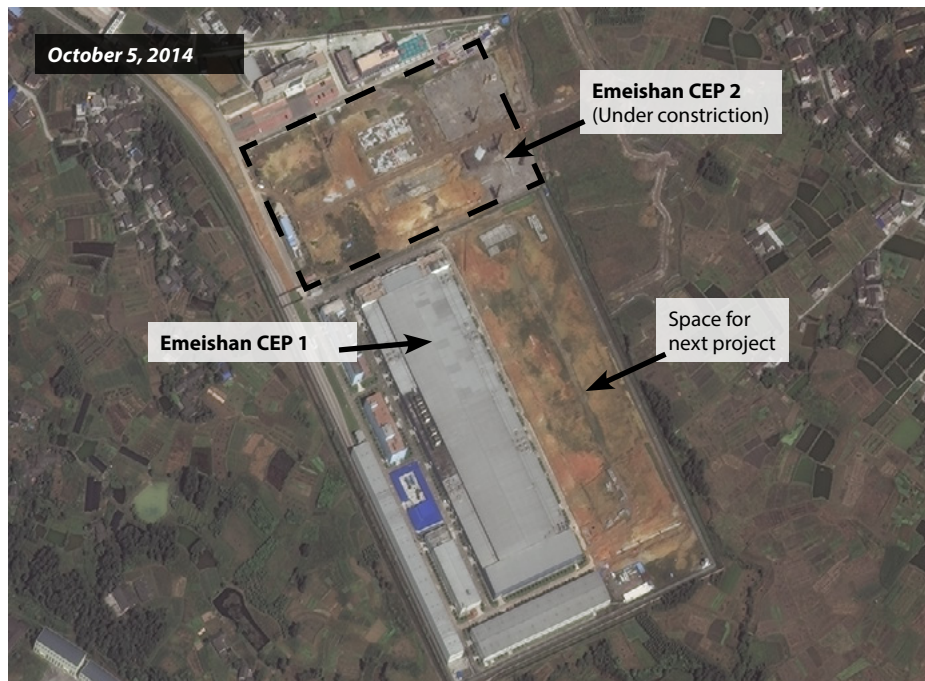
Note: Heping uranium enrichment plant of Plant 814 at Jinkouhe. Satellite image from September 28, 2013 (Coordinates: 29°13'58.49" N/103°03'49.95" E). Source: DigitalGlobe

Figure 8: **The Emeishan Centrifuge Facility at Shuangfu, Plant 814, Emeishan City**



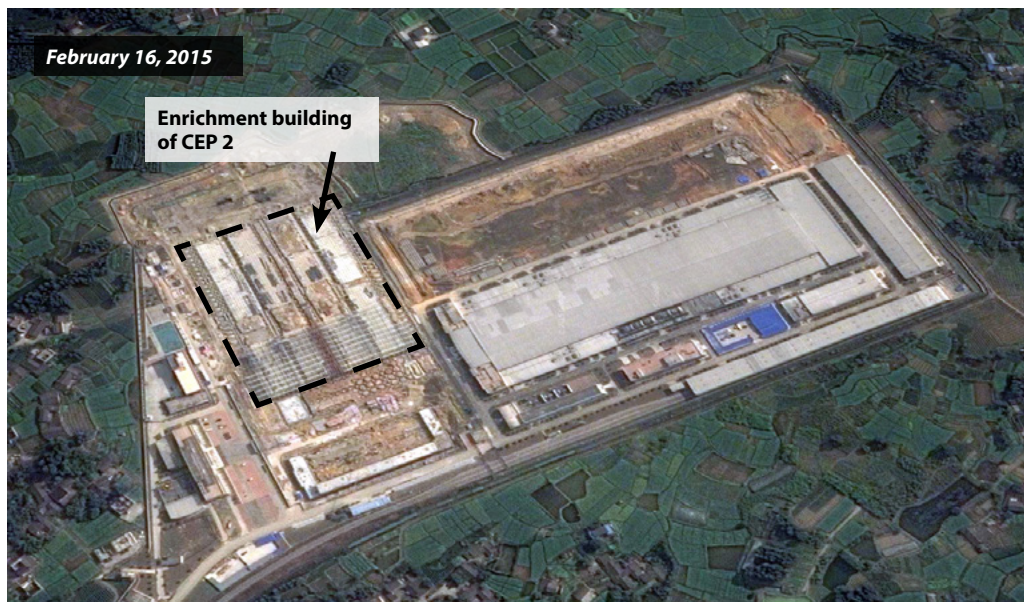
Source: CNES / Astrium (Google Earth)

Figure 9: **Emeishan CEP 1 and CEP 2 of Plant 814 at Emeishan City**



Note: Satellite image from October 5, 2014 (Coordinates: 29°40'38.33" N/103°32'04.65" E). The image shows CEP2 under construction. Source: DigitalGlobe

Figure 10: **Emeishan CEP 1 and CEP 2**



Note: The image shows significant progress on construction of CEP2. Satellite image from February 16, 2015. Source: CNES / Astrium (Google Earth)

V: CAN CHINA'S ENRICHMENT CAPACITY MEET COMMERCIAL SWU DEMAND?

To estimate Chinese SWU requirements, we assume the following: first, China's total nuclear capacity increases linearly from 20 GWe in 2014 to 58 GWe by 2020 (based on China's current official plan for nuclear development through 2020). Second, given the current dominance of PWR designs, we assume that in practice these reactors will account for the majority of China's nuclear growth; the exceptions are the two CANDU reactors (2 x 728 MWe). Finally, from 2014 to 2020, we assume that PWRs will have an average burn-up rate of about 50 GWd/t,⁸⁴ and an annual LEU requirement per GWe PWR of about 18.8 metric tons.⁸⁵

Then, the annual SWU requirement per GWe PWR would be about 129 metric ton-SWU (1000 kg-SWU).⁸⁶ In addition, we assume that producing the initial core for each new reactor will require the equivalent of about three times the annual SWU requirement. Consequently, as shown in figure 11, we can estimate that the annual SWU requirement will increase to about 9 million SWU in 2020 from about 3 million SWU in 2014.⁸⁷

As discussed above, China had a total enrichment capacity of about 4.5 million SWU/year in 2014, and will have a total capacity of 5.7 million SWU/year by the end of 2015. If the Emeishan CEP 2 with an estimated capacity of around 0.8 million SWU/year is operational around 2016, and if CNNC adds around a million SWU/year of additional capacity each year, then China should face no challenges in supplying a total capacity of about 12 million SWU/year by 2020. Indeed, the Lanzhou and Hanzhong plants, and the Emeishan facility of Plant 814 each apparently intend to build more capacity. Figure 11 shows projected annual enrichment capacity through 2020.

84 In 2003, NNSA approved the Daya Bay Nuclear Power Plant's application to increase its maximum burnup from 47 to 52 GWd/t (see: NNSA Notice No. 95, Sep. 2, 2003, http://www.mep.gov.cn/info/gw/haqwj/200309/t20030902_89437.htm). It is reported that the PWRs at Daya Bay, LingAo, and the early M310 to CPR-1000 reactors have an average burnup of 43 GWd/t and a maximum of 50 GWd/t. The PWRs of LingAo Phase II, Hongyahe, Ningde, and Yangjiang have an average burnup of 50 GWd/t and a maximum of 57 GWd/t. (See: WNA, "China's Nuclear Fuel Cycle (Updated April 2015)").

85 The annual LEU requirement per GWe PWR is obtained as, $M = P \cdot CF \cdot 365 / (\mu \cdot B)$, where M is the mass of LEU required per year (MTHM/year); P is the installed electric capacity (GWe); CF is the capacity factor, taken as 85% here; μ is the thermal efficiency, taken as 33% taken here; and B is the burnup of spent fuel (GWd/MTHM).

86 Producing one kilogram of LEU product enriched to 4.5% will require 6.87 kg-SWU with natural uranium feed for tails at 0.25%.

87 To estimate SWU demand in 2014, I assumed total nuclear capacity of 20 GWe in 2014 by adding 3 GWe PWRs of new capacity to the total of 17 GWe in 2013, as we should include SWU for the new cores. In addition, to get the total nuclear capacity of 20 GWe we need to subtract about 1.5 GWe of the two CANDU reactors (which do not need SWU), i.e., a net total is 18.5 GWe for SWU requirement.

Based on figure 11, we can estimate the cumulative SWU requirement from 2014 to 2020 to be about 44 million SWU, and the cumulative SWU domestic supply to be about 58 million SWU during the same period. This indicates China could have a supply of enrichment capacity about 30% greater than its cumulative requirements in that timeframe.

In addition, as mentioned above, when China purchases foreign reactors, it often requires foreign vendors to supply the first few subsequent loads of reactor fuel. These deals further save China SWU. The following commitments are examples of such requirements:

- AREVA will supply fresh fuel for 15 years for its two exported EPRs at the Guangdong Taishan nuclear power plant.⁸⁸
- Westinghouse will supply the first loads for its four AP1000 reactors sold to China.⁸⁹ Enriched uranium products for the same four AP1000 reactors will be supplied by Tenex of Russia from 2010 to 2021, under a 2008 agreement.⁹⁰ Further sales of AP1000 reactors can be expected.⁹¹
- URENCO supplies 30% of the enriched uranium for the two Daya Bay reactors in Guangdong.⁹²
- Russia's TVEL will supply the fuel for Tianwan 3 and 4 (two VVERs) until 2025.

Eventually, the total SWU saved by China through those foreign LEU supply deals will amount to around 14 million SWU during the period between 2014 and 2020 (see table 3). In addition, CGN's recent deal with Kazakhstan to import enriched product would further save China's SWU.⁹³ While some Western publications suggest that China's nuclear power industry relies considerably on imported SWU,⁹⁴ imported SWU will account for only one third of total SWU demand through 2020, and will be equal to about one fourth of cumulative domestically supplied SWU through 2020. Given that China has sufficient

88 AREVA, "Taishan 1&2—China," AREVA website, n.d., <http://www.AREVA.com/EN/operations-2404/china-taishan-12.html#tab=tab4> (accessed June 25, 2015).

89 Rob Pavey, "SC Plant Readies Nuclear Fuel for China's First AP1000 Reactor," *The Augusta Chronicle*, March 22, 2012, (last updated March 23, 2012), <http://chronicle.augusta.com/news/business/2012-03-22/sc-plant-readies-nuclear-fuel-chinas-first-ap1000-reactor>

90 WNA, "China's Nuclear Fuel Cycle (Updated April 2015)."

91 Brian Wang, "China Looks to Buy 8 More AP1000 Nuclear Reactors and is Accelerating Nuclear Reactor Approvals," *Next Big Future* (website), April 21, 2014, <http://nextbigfuture.com/2014/04/china-looks-to-buy-8-more-ap1000.html> (accessed June 25, 2015).

92 WNA, "China's Nuclear Fuel Cycle (Updated April 2015)."

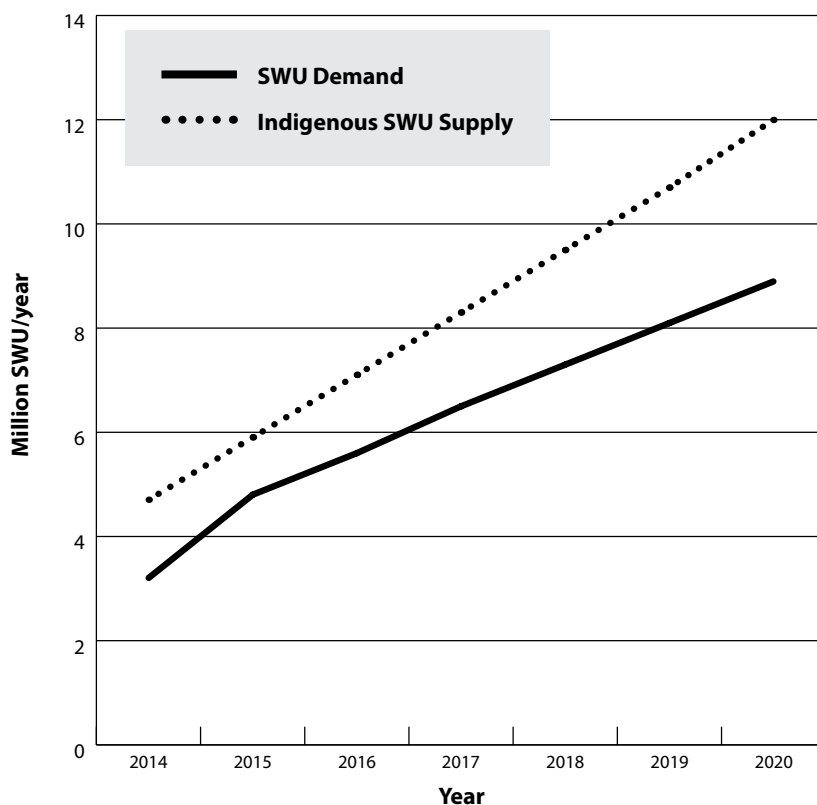
93 Phil Chaffee and Kevin Pang, "Washington Spot Price Weakens Again While Producers Shrug."

94 WNA, "China's Nuclear Fuel Cycle (Updated April 2015)."

enrichment capacity to meet SWU demand, the more pressing rationale for importing SWU is to save the country's own uranium resources.

Consequently, China will have a total surplus of around 28 million SWU through 2020, which it could sell on the international market. This is consistent with CNNC's policy of "meeting its domestic demand and targeting the international markets" in supply of enrichment services.⁹⁵ China has been pursuing a fully independent enrichment capability, which includes 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 plans for nuclear power development, "enrichment technology must be completely independent. So far, China has had the ability to manufacture centrifuges that can fully meet the subsequent needs of nuclear power development...On the basis of securing its domestic supply [of SWU], CNNC will gradually expand its foreign markets, and make China's nuclear fuel industry internationally competitive."⁹⁶

Figure 11: **Projection of China's SWU Supply and Demand (2014–2020)**



⁹⁵ Li, "Status and Future of the Front-end of China's Nuclear Fuel Cycle."

⁹⁶ Yu, "A Completely Independent Uranium Enrichment Technology."

| Table 3: SWU Supply by Foreign Firms for Select Imported Reactors | | |
|---|--|--|
| Supplier | Deals | Saved SWU for China (2014–2020) (million SWU) ¹ |
| AREVA, for two EPRs at Taishan nuclear power plant | Taishan 1 and 2 (two 1075 MWe PWRs), under construction; AREVA to supply fresh fuel for 15 years. Assuming operations begin in 2016 and 2017, respectively. | 4 |
| Westinghouse, for four AP1000s | Sanmen 1 and 2, Haiyang 1 and 2 (four 1250 MWe PWRs); Westinghouse to supply four cores. Assuming operations begin around 2016. | 1.9 |
| Russia's Tenex, for the above AP1000s | Based on the former plan: Tenex to supply 10 years of fuel for the above four AP1000s from 2010 to 2021. However, given the delay before these reactors are in operation, supplied SWU pre-2020 could be less than the original planned for as noted here. | 6 |
| URENCO, for Daya Bay | Daya Bay 1 and 2 (two 984 MWe PWRs); URENCO to supply 30% of fuel. Assuming deal to continue through to 2020. | 0.5 |
| Russia's TVEL, for VVERs | Tianwan 3 and 4 (two 1060 MWe PWRs), under construction. Assuming operations begin in 2016 and 2017, respectively. TVEL will supply LEU until 2025. | 1.8 |
| | | Total: 14.2 |

VI: CONCLUSIONS

While considerable uncertainty remains, 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, and may have the ability to add 1 million SWU/year of additional capacity annually. China already has much more enrichment capacity than previously thought, and even more is on the way. For instance, the WNA still estimates that China has only a total capacity of 2.2 million SWU/year. In fact, China has enough enrichment capacity to meet its nuclear power fuel requirements for the coming decade and beyond. Assuming my estimates are correct, China will have excess enrichment capacity and will become a net exporter of commercial enrichment services. The development of China's enrichment capacity has been consistent with the government's stated policy of "self-sufficiency" and "targeting the international markets" in the supply of enrichment services.

CNNC nuclear experts also state that the separation capacity of Chinese centrifuges is greater than that of the centrifuges supplied by Russia under the first three phases of the China-Russia agreements.⁹⁷ China's uranium enrichment experts further emphasize that CNNC is developing a new generation of more advanced and economic centrifuges, and has made significant progress with the key technological challenges.⁹⁸

Finally, in light of this surge in enrichment capacity, China should address international concerns about the proliferation implications of its development of centrifuge technology. Specifically, Russian-designed centrifuges (subcritical centrifuges) pose particularly significant proliferation challenges because of the relative ease with which cascades can be reconfigured through valve manipulation.⁹⁹ China has issued several regulations on nuclear export controls. For instance, in 1997, China issued the "Regulations on the

97 Communications with CNNC nuclear experts in October 2014. If Chinese models have the same number of shelves per stack as in the Russian-supplied facilities and there is a proportional relationship between enrichment capacity and the floorspace of the main enrichment hall, then the Russian-supplied centrifuge facilities built under the first three phases would produce around 20 SWU per square meters, and the Chinese indigenous facilities would produce an average of around 28 SWU per square meters—about 40% more than the Russian facilities. Though speculative, this comparison would seem to support the Chinese experts' statements.

98 "Lei Zengguang: China has Realized its Uranium Enrichment Autonomy."

99 Oleg Bukharin, "Understanding Russia's Uranium Enrichment Complex."

Control of Nuclear Export,” which were updated in 2006. In 1998, China issued the “Regulations on the Control of Nuclear Dual-Use Items and Related Technologies Export,” and updated them in 2007. In 2009, the Ministry of Commerce promulgated the “Measures for Administration of Dual-use Items and Technologies Subject to Export General License” to further strengthen the country’s licensing system for export control. However, the government should take further measures to assure effective implementation and enforcement of these regulations and policies.

ABOUT THE PROJECT ON MANAGING THE ATOM

The Project on Managing the Atom (MTA) is the Harvard Kennedy School's principal research group on nuclear policy issues. Established in 1996, the purpose of the MTA project is to provide leadership in advancing policy-relevant ideas and analysis for reducing the risks from nuclear and radiological terrorism; stopping nuclear proliferation and reducing nuclear arsenals; lowering the barriers to safe, secure, and peaceful nuclear-energy use; and addressing the connections among these problems. Through its fellows program, the MTA project also helps to prepare the next generation of leaders for work on nuclear policy problems. The MTA project provides its research, analysis, and commentary to policy makers, scholars, journalists, and the public.

The Project on Managing the Atom

Belfer Center for Science and International Affairs

John F. Kennedy School of Government

Harvard University

79 JFK Street; Mailbox 134

Cambridge, MA 02138

Phone: 617-495-4219

E-mail: atom@hks.harvard.edu

Website: <http://belfercenter.org/mta>



Belfer Center for Science and International Affairs

Harvard Kennedy School

79 JFK Street

Cambridge, MA 02138

Fax: (617) 495-8963

Email: belfer_center@hks.harvard.edu

Website: <http://belfercenter.org>

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