

PROJECT ON MANAGING THE ATOM

CHINA'S ACCESS TO URANIUM RESOURCES

BY HUI ZHANG AND YUNSHENG BAI



HARVARD Kennedy School

BELFER CENTER for Science and International Affairs

MAY 2015

Report by the Project on Managing the Atom

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

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

Paper No: 2015-03

The authors of this report invite liberal use of the information provided in it for educational purposes, requiring only that the reproduced material clearly cite the source, using:

Zhang, Hui and Bai, Yunsheng, “China’s Access to Uranium Resources” (Cambridge, Mass.: The Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard University, May 2015).

Design & Layout by Josh Anderson

Cover Photo: The Rossing uranium mine in Namibia, one of the largest open pit uranium mines in the world, near to where an overseas project of the China National Nuclear Corporation is building a new mine. Credit: Conleth Brady/IAEA

Copyright 2015, President and Fellows of Harvard College
Printed in the United States of America

PROJECT ON MANAGING THE ATOM

CHINA'S ACCESS TO URANIUM RESOURCES

BY HUI ZHANG AND YUNSHENG BAI



HARVARD Kennedy School

BELFER CENTER for Science and International Affairs

MAY 2015

About the Authors

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 Atomic Scientist*, *Disarmament Diplomacy*, *Disarmament Forum*, *the Non-proliferation Review*, *Washington Quarterly*, *Journal of Nuclear Materials Management*, and *China Security*.

Yunsheng Bai is a Senior Research Fellow and the Assistant Dean of the China Institute of Nuclear Information and Economics (CINIE), where he is also the Director of the Reform and Development Research Center. He received a bachelor's degree in engineering from the East China Institute of Geology in 1987 and a master's degree in economic management from Central Party School in 2002. From 1987 to 2000, he worked as a senior engineer in Geo-physical and Geo-chemical center of Beijing Research Institute of Uranium Geology. He has worked at CINIE since 2001. His research focuses primarily on nuclear industry strategic planning, relevant policies and regulations, and economics of nuclear energy. He has published numerous academic papers and reports and is co-author of a number of influential books.

Acknowledgments

The authors are grateful to the group of Chinese nuclear experts who participated in the interviews during the preparation of this report. The authors also would like to thank a number of colleagues who provided helpful comments and suggestions, particularly including Mathew Bunn, Martin Malin, Frank von Hippel, Erich Schneider, and Dan Collier. We thank Josh Anderson, Xiaodon Liang, and Nate Sans for their help in the preparation of the report. Finally, we would like to thank the Carnegie Corporation of New York and the John D. and Catherine T. MacArthur Foundation for financial support of this work.

Table of Contents

Executive Summary.....	vii
Introduction.....	1
I. China's Nuclear Power Development.....	3
II. China's Growing Uranium Demand.....	7
III. The Status of China's Uranium Resources and Analysis of Uranium Potential.....	11
The Historical Development of China's Uranium Industry.....	11
Characteristics of China's Uranium Deposits.....	15
China's Known Uranium Resources.....	16
Uranium Production in China.....	23
Analysis of the Situation and Prospects for China's Uranium Resources.....	25
IV. China's Pursuit of Uranium Abroad.....	29
Chinese Purchases of Uranium Worldwide.....	30
Available Surplus from Past Imports.....	32
Enriched Uranium Supplies.....	33
China's Overseas Exploration and Mining Activities.....	34
V. Security of Uranium Supply and World Uranium Resources.....	43
World Uranium Resources.....	43
World Market for Uranium Resources.....	52
The Relatively Low Price of Uranium over the Long Run.....	56
Strategic Uranium Storage.....	59
VI. Recommendations.....	63

Executive Summary

By the end of 2014, China had 22 power reactors (20 GWe) in operation with 26 units under construction (27 GWe), leading the world with the pace of its reactor 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)," which envisions China's total nuclear capacity to be 58 gigawatts-electric (GWe) in 2020, with another 30 GWe under construction at that time. Whether or not China meets its official goal, within a few decades, China is expected to operate more nuclear power plants than any other country in the world. Based on the currently used once-through fuel cycle, as capacity increases the nuclear industry will demand more uranium. Concerned about security of uranium supply, some Chinese nuclear experts have actively advocated the expansion of plutonium reprocessing and recycling as a means of "saving uranium." However, the findings of this report suggest that between China's domestic uranium mining, uranium purchased on the international market, and uranium mined by Chinese-owned companies overseas, the security of its uranium supply would not pose any serious challenge to China's nuclear power development, even under the most ambitious scenarios, up to at least the middle of the 21st century, thus avoiding the need to commit to the current generation of expensive and troublesome reprocessing technology.

China's Growing Uranium Demand

Any estimate of China's future uranium demand depends upon accurate projections of the number, size, and type of China's nuclear power facilities it will build.

Under the most optimistic high-growth scenario, China's nuclear-generating capacity would increase 20 fold, from 20 GWe in 2014 to 400 GWe by 2050—connecting around 10 new reactors to the grid every year and producing about 15% of all of China's electrical generation. The 400 GWe by 2050 target is about four times more than the current U.S. capacity and close to the current output of the total number of operational reactors worldwide (the worldwide total in 2014 was about 377 GWe). Thus, this high growth scenario is assumed to be the upper limit of possible Chinese nuclear growth. Consequently, we estimate that at most, China might use a total of approximately one million metric tons of uranium (1 MtU) from now until 2050. Under the high growth scenario China in 2050 will require as much uranium each year as the entire world does today.

Under a low-growth scenario, China's nuclear fleet would go from a total installed capacity of 20 GWe in 2014 to 130 GWe by 2050 (about 5% of its total electricity generation). In this case, we estimate China's cumulative requirements for uranium will be approximately 0.5 MtU through 2050.

Historical Development of China's Uranium Industry

Since 1955, China's uranium industry has developed through four major stages.

Early Development (1955–1970)

China launched its uranium industry in 1955 at the same time as the initiation of its nuclear-weapons program. In 1958, China established its first set of uranium mines and a milling plant. During the early 1960s, large-scale uranium prospecting projects were initiated in several major regions. By the mid- to late 1960s, the primary focus of uranium exploration had shifted from the northwestern to the southern region of the country.

Boom Development for Military Purposes (1971–1985)

During the 1970s, China rapidly increased its exploration activities, primarily to secure uranium for the defense sector. In 1978, China's annual drilling efforts reached a peak of around 1,550 kilometers. However, as Beijing began to give priority to economic and political reforms initiated in 1978, China's uranium exploration effort began to decline gradually. Meanwhile, China's uranium industry began to shift its focus from military purposes to civilian nuclear energy.

Retraction and Adjustment (1986–2003)

During the late 1980s China deepened its “shift from military to civilian” in the nuclear industry, and domestic uranium exploration and mining activities began to shrink. From 1986 to 2003, this trend continued mainly because the uranium requirements of the defense sector were significantly reduced, and there was no urgent demand from the country's modest nuclear power program.

Revival and Acceleration (2004–Present)

Since 2004, China's state policy guiding the development of nuclear power changed and officially endorsed increasing the pace of growth from “moderate” to “active” development. To meet expectations of a rapid increase in uranium requirements, uranium prospecting and exploration in China accelerated greatly, both in terms of expenditures incurred and meters drilled. As a result, China's uranium resources have increased almost three-fold since 2004.

To secure supplies of uranium fuel for its quickly-expanding nuclear power plans, the central government has taken a number of measures to intensify uranium exploration and mining in China, including increasing government investments and allowing involvement by organizations other than the China National Nuclear Corporation (CNNC). The government has also endorsed a strategy of “two markets and two resources,” referring to the Chinese market and the world market, and uranium purchased from overseas and uranium produced in China.

In the past, China's uranium exploration activities have experienced “up and down” periods, mainly due to inconsistent nuclear power plans over time. For the past three decades, China has lacked a long-term, centrally designed strategy (i.e., a comprehensive national nuclear power plan) for nuclear power development. The role of nuclear power in the nation's energy system has since swung from being a supplemental source of energy to an envisioned major source, which seriously affected the government's and industry's efforts in uranium-related work.

China's Uranium Procurement Strategy

Since 2004, China's annual uranium requirements have been increasing faster than its domestic production capacity. In recent years, domestically produced uranium can meet only around one-third of annual uranium requirements, and this situation is not expected to change significantly in the near future.

Given the big gap between demand and domestic production of uranium, some Chinese experts argue that China's lack of uranium will constrain development of its nuclear power industry. However, domestic uranium production capacity is not the same thing as a secure supply capacity. China has been discovering new uranium resources each year in multiples of the amounts it consumes. This trend is expected to continue in the near future.

China could increase uranium production more rapidly than it has in the past. However, a majority of the uranium ore discovered in China is of poor quality and will be costly to mine in comparison to that in other countries. Hence, China has instead taken advantage of low international uranium prices. China prefers to save its own proven domestic uranium resources for supply security in the future.

To secure the resources needed, for the past 10 years the central government has adopted a strategy that combines domestic production, overseas exploitation, and purchases of uranium in world uranium markets. Known as the "Three Thirds" rule, one-third of its uranium comes from domestic supply, one-third from direct international trade, and another third from overseas mining by Chinese firms.

Domestic Uranium Supply

Over the past decade, China's demand for uranium has outstripped its domestic supply. But its identified conventional resources have also grown dramatically over the same period, China's uranium potential is great, and its production has been sufficient to supply about one-third of China's current needs.

China's Known Uranium Resources: According to *Uranium 2014: Resources, Production, and Demand* (Red Book), as of January 1, 2013, China's identified conventional uranium resources totaled 265.5 ktU (thousand metric tonnes uranium), a more than three-fold increase from 85 ktU in 2004 due to increased investment in exploration over the past decade.

However, the known uranium resource is a dynamic economic concept. Its size will depend on a number of factors, including technological advances, engineering feasibility, exploration expenditures, uranium prices, and limitations of ore grade.

If China continues to spend on exploration at the same average rate and average discovery cost of \$3.2/kg U as it did during the period between 2004 and 2012, then China could expect to identify around 1.1 MtU by 2050.

China's Uranium Potential: Based on uranium metallogeny, new models, and exploration data from the past several decades, recent predictions indicate that China could have over 2 million tonnes of potential uranium resources.

There are several major reasons to support predictions of a very large uranium potential. China still has huge areas awaiting exploration. About two-thirds of China's total area have seen only very low levels of exploration work or even no attention at all. Moreover, a big resource potential could lie at a greater depth. Most of China's current identified resources are located at a depth of less than 500 meters. However, the exploration experiences of other nations have shown that uranium resources can be located in much deeper areas than 500 meters. Further, China has favorable geological conditions for uranium mineralization, including East China's important position on the uranium metallogenic belt of the Pacific Rim, and North China's important position on the Eurasian uranium metallogenic belt.

China's Pursuit of Overseas Uranium

To supplement domestic production of uranium, China engages in international trade and controls extensive overseas mining operations.

Since 2006, both CNNC and the China General Nuclear Power Corporation (CGN) have been aggressively pursuing overseas uranium supplies. As a result, China has recently secured a huge amount of overseas uranium resources—about three times the size of its own known uranium resources. And more could easily be added, which would make for more than enough to meet its most ambitious nuclear energy plan by 2050.

International Trade: Based on available information, CNNC and CGN will have a total of approximately 130 ktU available from international trading deals for the period between 2014 and 2050, coming from long-term supply contracts with companies such as Canada's Cameco, Kazakhstan's Kazatomprom, France's AREVA, Uzbekistan's Navoi Mining & Metallurgy, and from other contracts. Most of the current contracts will end around 2020. If China wants, it could generate new contracts before 2050. Meanwhile, China can purchase uranium on the open spot market. Thus, China would have much more overseas uranium available for the period of planned expansion through international trade than the quantities estimated in this report.

China also has surplus uranium available from past imports. Between 2006 and 2013, China imported 73 ktU; this figure is about three times more uranium than it needed for its domestic energy use. When the uranium that came from Chinese mines during that same time period is taken into account, the resulting total surplus is about 60 ktU.

Furthermore, when China purchases foreign reactors, it often requires the foreign vendors to supply the first few loads of low-enriched uranium (LEU) fuel. These deals further save Chinese uranium resources. Eventually, we estimate the total uranium saved by China through such LEU supply deals will amount to around 40 ktU.

Taken altogether, between 2014 and 2050 foreign-origin uranium acquired through trading and LEU supply deals will have reduced Chinese natural uranium requirements by at least 230 ktU. It should also be noted that this number will likely increase as additional deals are made.

China's Overseas Exploration and Mining: For the past several years, CNNC and CGN have been actively exploring for, and mining uranium in countries like Niger, Namibia, Zimbabwe, Kazakhstan, Uzbekistan, Mongolia, and Australia.

By the end of 2009, CNNC stated that it had already secured more than 200 ktU in overseas resources. While it did not disclose details about the size of the secured overseas resources, our estimate based on available information from independent sources is consistent with CNNC's statement.

In 2013, CGN stated that it had secured approximately 308 ktU from overseas resources and that more would be acquired. Available information from independent sources suggests their number is also correct.

These resources that China has already secured represent over 500 ktU of resources (likely 400 ktU of recoverable uranium); but between now and 2050, it may well be possible for China to enter into additional agreements that would secure still more resources.

Combined with the 230 kt uranium available from trading on the international market and LEU deals, it is likely that a cumulative total of 630 kt of overseas uranium will be available for China's nuclear power development from 2014 to 2050.

Feeding China's Nuclear Power Development

There are around 200 ktU recoverable domestically in China at a cost of less than \$130/kgU, which would be sufficient to support even the high-growth scenario through 2030. Combined with the 230 ktU available from trading on the international market and the LEU deals, a total of approximately 430 ktU will be available at relatively low price and would be sufficient to meet China's ambitious nuclear plan up to 2040.

However, if China continued to spend on exploration at the same average rate as it did during the period between 2004 and 2012, with the same average discovery cost of \$3.2/kg U, then China could expect to identify around 1.1 MtU (*in situ* resources) by 2050 (i.e., around 843 kt recoverable uranium resources), close to the uranium demand even under the high-growth scenario (i.e., 950 ktU). Thus, combined with locked overseas uranium (230 ktU) through trade and foreign supply of LEU, China would have around 1 MtU by 2050, which would be enough to meet its needs.

Further, over 400 ktU will be secured through overseas exploration and mining and can be added to the national stockpiles. Thus, even without new domestic discoveries, a total supply of 830 ktU (i.e., 200 ktU of currently identified domestic uranium and 630 ktU of overseas uranium) will be available to meet a projected demand of 660 ktU under the high-growth scenario through 2045. However, demand might not be met through 2050, with projected capacity at 400 GWe requiring cumulative total uranium of about 950 ktU. However, the gap of 120 ktU would easily be filled by continuing increases in new domestic discoveries and expansion of overseas mining and imports. Consequently, China's domestic and overseas uranium would be sufficient to supply its nuclear power development even under the high-growth scenario beyond 2050.

Security of World Uranium Supply

The global distribution of uranium resources and nuclear power capacity is highly suited to trade complementarity: those states with the most nuclear power generally have less uranium,

and those states that have the most uranium generally don't have that much nuclear power. The trade in uranium resources, therefore, naturally takes place in a global market place. Unlike oil and natural gas resources which are distributed fairly unevenly in certain geographical locations, sources of uranium are diverse both geographically and politically, and collusion to raise prices and/or limit supplies would be unlikely.

The 2014 “Red Book” report on global uranium resources, production, and demand estimates that as of January 1, 2013, total identified global uranium resources amounted to 7.6 Mt in the highest cost category (\$260/kgU or less), an increase of 7.6% compared to the total reported in 2011. This increase within two years adds almost ten years of global reactor supply to the existing resource base. Based on uranium requirements in 2012 (about 61,600 tU/year), if there was no growth of nuclear power, total identified resources would be sufficient for about 124 years of supply to the global nuclear power fleet.

Combined with the undiscovered resources (prognosticated resources and speculative resources), the total conventional uranium potential (total identified uranium plus total undiscovered resources) would be around 20 MtU, which would be sufficient for over 300 years of supply for the global nuclear power fleet at 2012 uranium requirement levels. Further, there also exist considerable unconventional resources, including phosphate deposits, black shale, and coal ash. It is estimated that worldwide totals of phosphate-related resources could contain as much as 22 MtU. In addition, the world's oceans contain around 4.5 billion tU, sufficient for over 70,000 years of supply for the global nuclear power fleet at 2012 uranium requirement levels. Hence, if technology develops to allow seawater uranium to be recovered economically, seawater uranium would be an almost inexhaustible natural resource.

The past experience indicates that global identified uranium resources have more than doubled since 1975, in line with increasing expenditure on uranium exploration, even as over 2 MtU have been used.

Moreover, historical trends in the price of uranium suggest that past predictions of a steady rise in the price of uranium have been wrong. The 2011 MIT study, “The Future of the Nuclear Fuel Cycle” emphasizes that “there are good reasons to believe that even as demand increases, the price of uranium will remain relatively low.” This is in line with other studies showing that the prices of most minerals have actually decreased in constant dollars over the past century, even while extraction increased.

Even if uranium prices were to see large increases, the busbar cost of nuclear electricity would not increase substantially as the cost of uranium accounts for only a small fraction of total nuclear electricity production costs. In the recent past, uranium has generally accounted for only about 2–4% of the lifetime-levelized busbar cost of nuclear-generated electricity.

Strategic Uranium Storage

If China became seriously concerned about potential disruptions of its uranium supply, it could easily and inexpensively establish a strategic uranium stockpile, much like its strategic oil reserve. In fact, since 2011 a strategic uranium storage plan has been under consideration as a national energy project, and was proposed in the China's Twelfth Five-Year Energy Plan. To

support a strategic uranium storage program, China's government could establish a strategic uranium reserve fund in the same way it established a Spent Fuel Management Fund in 2010. If the government began collecting monies for a strategic uranium reserve fund at \$1.4 mil/kWh (about one-third the rate that maintains the spent fuel fund), then a fund drawing from a fleet of 60 1 GWe pressurized water reactors (PWRs) for 30 years would be sufficient to support a 20-year supply of uranium for those reactors.

Recommendations

To secure long-term uranium supplies for its fast-growing nuclear power industry, China's central government should take a number of measures to intensify both domestic and overseas uranium exploration and mining, continue participation in international trading of uranium, and adopt a strategy to provide for the storage of uranium. Specifically, it should consider the following recommendations.

Intensifying Domestic Exploration

China has almost tripled its known uranium resources over the last decade. China still has space to increase both its drilling and expenditures. To identify more uranium resources, the government needs to do more, including:

- Put in place a long-term, stable, and effective strategic plan for its uranium industry, and consider how to integrate this plan into its broader nuclear energy goals.
- Encourage more players to enter the uranium exploration and mining industry, and create a mechanism for competition among those players. The government should also coordinate among players in the uranium industry and firms in other metal minerals businesses to avoid waste of uranium resources.
- Increase financial support, and encourage other private actors to participate in investing in uranium-related activities. China should also establish a dedicated fund for uranium exploration and mining activities.
- Invest more to improve estimates of the country's uranium potential by developing and applying new appraisal and prediction methods. The effort should focus on prospecting and exploration work in those areas that have been surveyed in very low detail or have never been covered, and on further exploration at depths beyond 500 meters and 1000 meters, and in areas surrounding known uranium belts and deposits.
- Increase efforts to identify more uranium resources, including by focusing on uranium prospecting and exploration in the northern China regions with uranium deposits suitable for *in situ* leaching. The government should also seek to expand discoveries of vein-type uranium deposits related to volcanic rock and granite in southern China, speed up identification of medium- and large-scale deposits, and increase minable uranium resources.
- Increase research and development (R&D) investment in certain areas, including uranium mineralization theory and models, exploration technology and physical detection equip-

ment, and production and processing methods for mining uranium. Moreover, the government should increase R&D on unconventional uranium resources (e.g., phosphate deposits) and extraction of uranium from sea water.

- Strengthen training programs and encourage the training of more professional and technical personnel for uranium work, and improve the integration of human resources capabilities in the industry.

Strengthening Overseas Exploration

China should continue to adhere to its policy of “going out” to secure more foreign uranium supplies. To effectively implement this policy, the government should take the following measures:

- Establish a dedicated state organization or council to implement the government’s strategy for the acquisition of uranium abroad. The council should unify management and guidance for Chinese companies engaging in uranium work abroad. The new organization should be responsible for coordinating work among Chinese companies and between Chinese companies and foreign countries or companies.
- Support (with financing and policy) China’s companies to enhance their competitive edge in global exploration and mining activities. Government support can take the form of financial investment, low-rate loans, and tax incentives for uranium work abroad. The state should also establish a foreign uranium development fund targeting exploration and mining of identified uranium resources.
- Strengthen regulations on uranium activities abroad, including laws on insurance of overseas investments in uranium exploration and mining. Also, to facilitate cooperation with foreign countries, China should take measures to assure that imported uranium is accountable and only to be used for civilian purposes.
- Increase investments in training professionals for the international uranium business, and invest in developing advanced technology and equipment for uranium work abroad.

Introduction

China has emerged as the central focus of the international nuclear industry due to its ambitious nuclear energy plans. This was true both before the Fukushima nuclear accident of March 11, 2011, and it remains true in its aftermath. China leads the world in the pace of its nuclear development and in new reactor construction. Beijing officially plans to increase its total nuclear capacity from the 20 GWe in 2014 (electric gigawatts, see Table 1.1) to 58 GWe by 2020, and much more expansion is under consideration for the coming decades. Based on the currently used once-through fuel cycle, as capacity grows, the industry will demand more uranium. Concerned about security of uranium supply, some Chinese nuclear experts have actively advocated the expansion of plutonium reprocessing and recycling capabilities for “saving uranium.”¹ At the same time, other scientists argue that China should constrain the development of its nuclear power industry to match the limitations of its domestic uranium resources.² Thus, whether uranium supply will affect the development of China’s nuclear power industry is a key issue.

The purpose of this report is to provide a better understanding of China’s demand for uranium, to describe the availability of domestic and overseas uranium, to examine the security issues related to uranium supply, and to recommend steps to secure long-term uranium supplies for China’s fast-growing nuclear power industry.

Structure of the Report

Section I reviews the development of China’s nuclear power industry. In Section II, we project demand for uranium to 2050 under two nuclear expansion scenarios: a high growth scenario with 400 GWe of installed capacity and a low-growth scenario with 130 GWe of installed capacity.

In Section III, we review the development of China’s uranium industry, discuss characteristics of China’s uranium deposits and known uranium resources, and analyze the potential size of China’s uranium resources.

In Section IV, we examine China’s acquisition of overseas uranium. Using public information on recent uranium trade deals, we estimate how much uranium is available to China’s power industry through international trade, and how much is accessible through foreign uranium exploration and mining. We also estimate the quantity of available surplus uranium from past imports and enriched uranium supply transactions.

In Section V, we discuss supply security issues. We examine how much uranium is available globally, whether China can access those resources, and whether those resources will be available at an affordable cost in the long term. We also discuss uranium storage and saving strate-

¹ See, e.g., Xu Mi, “Fast Reactor Development for a Sustainable Nuclear Energy Supply in China” (presented at the Harvard-Tsinghua workshop on Nuclear Policies, Beijing, China, March 14, 2010); Gu Zhongmao, “Sustainable Nuclear Energy Needs Closed Fuel Cycle,” (presented at the Harvard-Peking Workshop on Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011).

² He Zuoxiu, “The Scarcity of China’s Uranium Resources Should Constrain its Nuclear Power and Build More Nuclear Warships,” *Scientific Chinese* (in Chinese), last modified October 11, 2011, http://news.ifeng.com/mil/4/detail_2011_10/11/9752834_0.shtml (accessed April 27, 2015).

gies, including the establishment of a strategic uranium reserve and reducing the assay of tails in enrichment.

Finally, in Section VI, we recommend measures to secure long-term uranium supplies to fuel China's ambitious plans for nuclear power, including intensifying uranium exploration and mining efforts both domestically and overseas, continuing participation in international trading of uranium, and adopting a uranium storage strategy.

We divided the writing of this report as follows: Yunsheng Bai was the lead author for sections on characteristics of China's uranium deposits and prospects for China's uranium potential in Section III. Hui Zhang was the lead author on other parts of the report, with contributions from Yunsheng Bai. We share responsibility for the recommendations of this report.

I: China's Nuclear Power Development

China has emerged as the central focus of the international nuclear industry due to its ambitious nuclear energy plans. This was true before the Fukushima nuclear accident on March 11, 2011 and has continued since then. China leads the world in terms of nuclear development pace and new reactor construction. By the end of 2014, China had 22 power reactors (20 GWe) in operation with 26 units under construction (27 GWe).³ China officially plans for its total nuclear capacity to be 58 GWe by 2020,⁴ and many more plants are under consideration for the coming decades.

In 2004, China's state policy guiding the development of nuclear power changed the officially endorsed pace of growth from "moderate development" to "active development." In March 2006, China's State Council approved the *Medium-and Long-term Nuclear Power Development Plan* (2005–2020), which set a national goal of increasing total nuclear capacity to 40 GWe by 2020. After 2008, China shifted from "active development" to "aggressive development."⁵ Projections for nuclear power then increased to 70–80 GWe by 2020.⁶ An authoritative study conducted in 2011 recommended that China install a nuclear power capacity of 200 GWe (about 10% of total electricity generation) by 2030 and 400–500 GWe (about 15% of total electricity generation) by 2050.⁷

The pace of nuclear development has slowed in the wake of Fukushima, however. In October 2012, after comprehensive safety inspections on all plants in operation and under construction, the State Council issued the new *Medium- and Long-Term Nuclear Power Development Plan* (2011–2020), which reconsiders nuclear safety and the pace of development.⁸ Based on this new nuclear development plan, China plans to grow its total nuclear capacity to 40 GWe by 2015 and 58 GWe by 2020 with a further 30 GWe under construction in that year.⁹ This represents a pace slower than the 70–80 GWe projected prior to Fukushima, although it is still faster than 40 GWe set in the 2006 official plan.

³ "China, People's Republic Of" International Atomic Energy Agency (IAEA), Power Reactor Information System, last modified April 26, 2015, <http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=CN> (accessed April 27, 2015).

⁴ 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).

⁵ Zhang Guobao, "Scientific Development of Electric Power Industry: the Pathway to Win the Challenge," *Journal of Qiushi*, (Chinese) No. 7, 2009.

⁶ See, e.g., Xinhua, "China Nuclear Power Installed Capacity Expected to Reach 70 GW by 2020, Scientists," February 11, 2011, http://news.xinhuanet.com/english/2009-11/02/content_12373871.htm (accessed May 3, 2015).

⁷ China Academy of Engineering, *China's Medium- and Long-Term Energy Development Strategy (2030, 2050)*, Science Press: Beijing, China, 2011.

⁸ 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/ldhd/2012-10/24/content_2250357.htm.

⁹ The Information Office of the State Council, *China's Energy Policy 2012*.

In practice, Chinese nuclear power development has been slowed down in the wake of Fukushima event. Many nuclear experts believe it would be very difficult to achieve the target of 58 GWe by 2020. Once again, recently some officials and nuclear experts address China's nuclear power development should be proceeded at a moderate pace under safety insurance.

To speed up establishing “clean, efficient, safe and sustainable” energy systems for China, the State Council published in June 2014 its *Energy Development Strategy Action Plan (2014–2020)*.¹⁰ It plans for non-fossil resources to account for 15% of Chinese electricity. It will speed up development of renewable sources including wind power to the level of 200 GWe and solar power of 100 GWe.¹¹ However, nuclear power remains at 58 GWe plus 30 GWe under construction as proposed in China's Energy Policy 2012, which means that China's pace of nuclear power development has been slowed relative to that of other renewable sources. In fact, in the wake of Fukushima accident, more Chinese are in favor of renewable energy.¹² It is not clear whether the central government will pursue an “aggressive” development of nuclear power in the future.

¹⁰ State Council of P.R. China, “Energy Development Strategy Action Plan (2014–2020),” June 7, 2014. http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm (accessed May 6, 2015).

¹¹ It should be noted that the capacity factors of wind and solar power are much lower than for nuclear power. For instance, capacity factor for wind power is around 20–25%, and about 15–20% for solar PV; but around 80–90% for nuclear power.

¹² GU Zhongmao, “Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China,” (presented at the Workshop on Alternative East Asian Nuclear Energy Futures, Singapore, October 15–16, 2014).

**Table 1.1: Nuclear Power Reactors in Operation in China
(at the end of 2014)**

Reactor	Type	Net capacity (MWe)	Gross Power (MWe)	First Grid Connection
Qinshan I-1	PWR (CNP300)	298	310	1991
Daya Bay 1	PWR (French M310)	944	984	1993
Daya Bay 2	PWR (French M310)	944	984	1994
Qinshan II-1	PWR (CNP-600)	610	650	2002
Lingao 1	PWR (French M310)	938	990	2002
Lingao 2	PWR (French M310)	938	990	2002
Qinshan III-1	PHWR (Candu 6)	678	728	2002
Qinshan III-2	PHWR (Candu 6)	678	728	2003
Qinshan II-2	PWR (CNP-600)	610	650	2004
Tianwan 1	PWR (VVER-1000)	990	1,060	2006
Tianwan 2	PWR (VVER-1000)	990	1,060	2007
Qinshan II-3	PWR (CNP-600)	620	660	2010
Lingao 3	PWR (CPR-1000)	1,026	1,080	2010
Lingao 4	PWR (CPR-1000)	1,026	1,080	2011
Qinshan II-4	PWR (CNP-600)	620	660	2011
Ningde 1	PWR (CPR-1000)	1,020	1,080	2012
Hongyanhe I-1	PWR (CPR-1000)	1,024	1,119	2013
Hongyanhe I-2	PWR (CPR-1000)	1,024	1,119	2013
Yangjiang 1	PWR (CPR-1000)	1,021	1,086	2013
Ningde 2	PWR (CPR-1000)	1,020	1,080	2014
Fuqing 1	PWR (CPR-1000)	1,020	1,080	2014
Fangjiashan 1	PWR (CPR-1000)	1,020	1,080	2014

Sources: International Atomic Energy Agency, “China, People’s Republic of,” Power Reactor Information System, last modified May 2, 2015, <http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=CN> (accessed May 3, 2015); World Nuclear Association, “Nuclear Power in China,” last modified April 27, 2015, <http://www.world-nuclear.org/info/Facts-and-Figures/World-Nuclear-Power-Reactors-and-Uranium-Requirements/> (accessed April 28, 2015).

II: China's Growing Uranium Demand

In this section, we project China's future uranium demand under two nuclear power expansion scenarios (see Figure 2.1):

High Growth Scenario

This scenario includes an increase in total installed capacity from 20 GWe in 2014 (about 2% of total electricity generation) to 58 GWe by 2020 (about 4% of total electricity generation).¹³ This scenario is based on China's current official plan through 2020, but also adopts a goal of 400 GWe by 2050 (about 15% of total electricity generation) from the 2011 study by the Chinese Academy of Engineering.¹⁴

The 400 GWe by 2050 target would constitute the most optimistic projection. It is about 20 multiples of China's current nuclear capacity (about 20 GWe), four multiples of current U.S. capacity (about 100 GWe)¹⁵ and close to the current output of the total number of operational reactors worldwide (the total is about 377 GWe by 2014). Thus, this high growth scenario could be taken as a bounding case.

Low Growth Scenario

This scenario includes an increase in total installed capacity from 20 GWe in 2014 to 58 GWe by 2020, but then attains a lower target of 130 GWe by 2050 (about 5% of total electricity generation). In practice, even this so-called low growth scenario represents substantial investment in nuclear capacity. China would have substantially more nuclear power in 2050 than the current U.S. capacity. However, given that most Chinese nuclear experts generally assume that at a minimum nuclear power will account for about 5% of total electricity generation by 2050, here we take the case as a low growth scenario.

To estimate the natural uranium requirements for the two scenarios, we assume:

- Given the current dominance of pressurized water reactor (PWR) designs and the high likelihood that new reactor constructions in China will be Gen III PWRs, we assume that in practice nuclear growth will be comprised primarily of PWRs;¹⁶ exceptions are the two CANDU reactors (2 x 728 MWe).

¹³ In practice, construction of some reactors has been delayed due to the Fukushima event, thus it would be difficult to arrive the goals for 2020. Some experts suggest China could install only 53 GWe or less by 2020 (based on communications with Chinese nuclear experts in Beijing, October 2014).

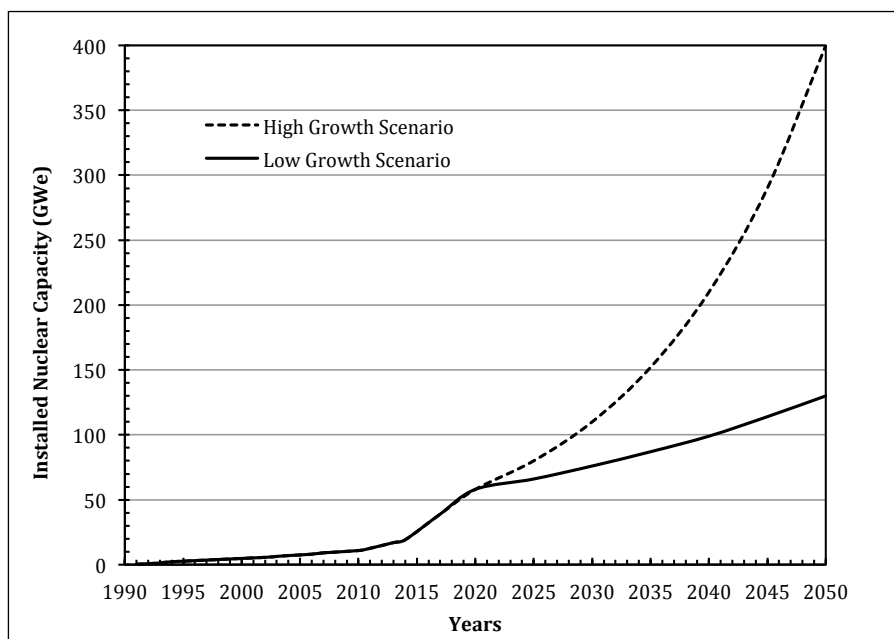
¹⁴ China Academy of Engineering, *China's Medium- and Long-Term Energy Development Strategy (2030, 2050)*.

¹⁵ Note that 100 GWe provides 21% of U.S. electric power. So China would be generating 5.6 times as much power as the U.S. does today. Per capita would also be more than the U.S. consumes today.

¹⁶ China has announced plans to construct reactors of other types as well, notably high temperature gas cooled reactors (HTR). A 210 MWe demonstration HTR-PM (HTR Pebble-bed Modular) unit is under construction at Shidaowan of Shandong province, and more are proposed at the same site (see World Nuclear Association, "Nuclear Power in China,"). There is also activity related to thorium fuel cycles in China. China plans to build a pilot 100 MWe molten-salt reactor by 2024 (See Mark Halper, "The U.S. is helping China build a novel, superior nuclear reactor" *Forbes*, February 2, 2015, <http://fortune.com/2015/02/02/doe-china-molten-salt-nuclear-reactor/> (Accessed April 28, 2015)). However, reactors of those types would account for a tiny portion of China's proposed installed nuclear capacity by 2050.

- From 2014 to 2020, we assume nuclear capacity will grow linearly, and that PWRs have an average burn-up of about 50 GWd/t.¹⁷
- From 2021 to 2050, we assume nuclear capacity also grows exponentially, and that new PWRs have an average burn-up of about 65 GWd/t.

Figure 2.1: Projected Nuclear Generation Capacity (GWe) for Two Scenarios (1991–2050)



Note: Nuclear installation from 1991 to 2014 is based on actual installed capacity, nuclear capacity from 2015 to 2020 is based on official plans, and projected capacity from 2021 to 2050 is based on assumptions provided in this report.

Table 2.1: The Annual LEU and Natural Uranium Requirement per GWe PWR (1000 tonnes)

Uranium	42GWd/t (U235 in fuel 4.0%)	50GWd/t (U235 in fuel 4.5%)	65GWd/t (U235 in fuel 5.0%)
LEU	22.4	18.8	14.5
Natural Uranium	182	173	149

¹⁷ Burnup (also known as fuel utilization) is a measure of how much energy is extracted from a primary nuclear fuel source. It is measured as the actual energy released per mass of initial fuel in gigawatt-days per metric ton of heavy metal (GWd/tHM), or similar units. In 2003, NNSA approved Daya Bay NPP's application to increase its maximum burnup from 47 to 52 GWd/t (see: National Nuclear Safety Administration, Approval of Daya Bay NPP application for increasing AFA-3G assemblies' burnup up to 53 GWd/tU, September 2, 2003. http://www.mep.gov.cn/info/gw/haqwj/200309/t20030902_89437.htm (accessed May 17, 2015)). It is reported those PWRs at Daya Bay, Ling Ao, and early M310 to CPR-1000 reactors have an average burn-up of 43 GWd/t with maximum of 50 GWd/t. For those PWRs of LingAo phase II, Hongyahe, Ningde, and Yangjiang have an average burn-up of 50 GWd/t with maximum of 57 GWd/t.(see World Nuclear Association, "China's Nuclear Fuel Cycle," last updated April 2015, <http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle/> (accessed April 28, 2015)).

Annual requirements of LEU¹⁸ and natural uranium¹⁹ per GWe PWR for different burnup and uranium enrichment rates is shown in Table 2.1.

To estimate the total annual natural uranium requirement in year t, the calculation should include the total natural uranium requirement in year t-1 (i.e., one year before year t) for the PWRs, the total natural uranium for the initial cores of the PWRs newly commissioned in year t, and the natural uranium for the two CANDU reactors.²⁰ Moreover, we assume after each PWR loads its initial core in year t, it needs in the following years about one-third of the initial fuel load of the reactor.

Consequently, we can estimate the annual and accumulated natural uranium requirements for the two growth scenarios between 2014 and 2050. Our results are shown in Table 2.2 and Table 2.3. Based on our projections, China would need between half a million and a million tons of uranium by 2050. Also it should be noted that under the high growth scenario China in 2050 will require as much uranium annually as the entire world does today (about 62 ktU).

Table 2.2: China's Projected Annual Uranium Demand (1,000 tonnes)

Scenario	2014	2020	2025	2030	2035	2040	2045	2050
Low Growth	5	12	10	12	14	16	18	20
High Growth	5	12	13	18	25	35	49	67

Table 2.3: China's Projected Cumulative Uranium Demand (1,000 tonnes)

Scenario	2014	2020	2025	2030	2035	2040	2045	2050
Low Growth	5	53	101	160	225	296	384	479
High Growth	5	53	111	191	301	454	663	952

¹⁸ 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 annual LEU requirement per year (MTHM/year); P is the installed electric capacity (GWe); CF the capacity factor, taken 85% here; μ is the thermal efficiency, 33% taken here; B is the burnup of spent fuel (GWd/MTHM).

¹⁹ The annual natural uranium requirement per GWe PWR is obtained as, $NU = M (X_p - X_t) / (X_f - X_t)$, where NU is the mass of annual natural uranium requirement of 1GWe PWR (tU); M is mass of annual LEU requirement per year (MTHM/year); X_p is the weight fraction of U-235 in the enriched uranium fuel, here we consider 4.0, 4.5, and 5% for 42, 50, and 65 GWd/t respectively; X_t is the weight fraction of U-235 in the waste stream, 0.25% taken here; X_f is the weight fraction of U-235 in the natural uranium, here, 0.711%.

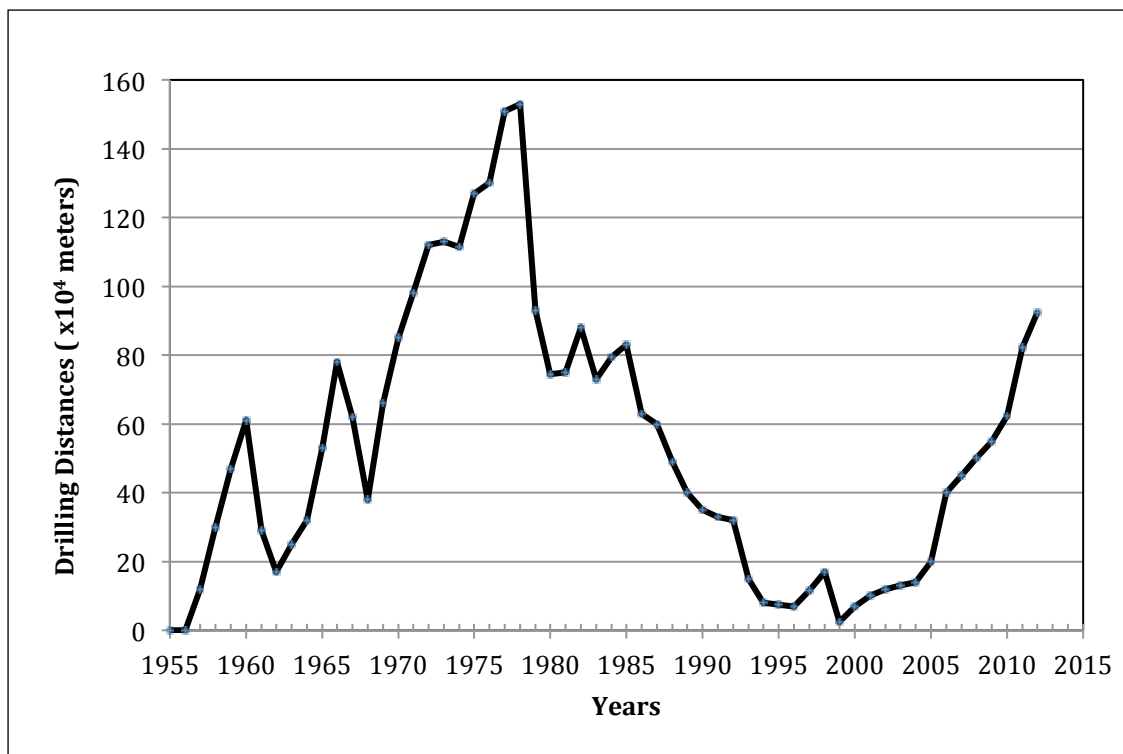
²⁰ For the Qinshan III CANDU-6 reactors with a natural uranium fuel cycle, we assume that the average discharge burn-up is about 7.5 GW d/t; the design capacity factor is 85%, and the thermal efficiency is 34%. Thus, the two CANDU reactors (2x728 MWe) consume about 177 tonnes natural uranium per year. Moreover, the two CANDU reactors (operated in 2002 and 2003 respectively) have the design life for 40 years. They are expected to operate for a longer time. Here we assume they operate through 2050. However, in any case, there are no significant changes for our estimates.

III: The Status of China's Uranium Resources and Analysis of Uranium Potential

The Historical Development of China's Uranium Industry

Since 1955, China's uranium industry has developed through four major stages (see Figure 3.1) with the focus shifting from the country's nuclear weapons program to nuclear power development. The stages were an early stage (1955–1970), a period of boom development for military purposes (1971–mid-1980s), a shrinking and adjustment stage (late 1980s–2003), and a revival (2004–present). During the boom development stage, annual drilling activity reached a peak of around 1550 kilometers. It fell to as little as 24 kilometers in 1999 during the shrinking and adjustment stage. Since 2005, to meet the requirements of its ambitious nuclear power plan, China has significantly increased its uranium exploration activities. During the eleventh Five-Year Plan (2006–2010), drilling averaged 520 kilometers per year; it has reached 800 kilometers per year since 2011.

Figure 3.1: History of Annual Drilling Distance (1958–2012)



Sources: Data between 1955 and 1999 is based on Yunsheng Bai, "China's Uranium Resources Situation," (presented at the Harvard-Peking Workshop on Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011). Data between 2000 and 2012 is based on Red Book data from 2001 to 2014: International Atomic Energy Agency (IAEA) and the Organization for Economic Co-operation and Development—Nuclear Energy Agency (OECD-NEA), *Uranium* [various years]: *Resources, Production, and Demand*, (Paris, France and Vienna, Austria: OECD-NEA, 1998–2014), all available at <http://www.oecd-neo.org/tools/publication?query=red+book&div=&lang=&period=100y&sort=title&filter=1#p7209> (accessed April 28, 2015).

Early Development (1955–1970)

China launched its uranium industry in 1955 at the same time as the start of its nuclear-weapons program. In 1958, China established its first set of uranium mines and a milling plant. During this initial stage (1955–1960), the Chinese team used the experience of the Soviet Union as a reference in its uranium reconnaissance work. Plans were made to prospect for uranium in Xinjiang and southern China, as these two regions exhibited geological conditions that were conducive to mineralization and were possessed by countries that had discovered uranium deposits.

During the early 1960s, large-scale uranium prospecting projects were initiated in several major regions, and the Chinese team also began to conduct research on the mineralization pattern of uranium. Significant achievements were made in prospecting for granite uranium deposits and carbonate-siliceous mudstone uranium deposits in southern China; more specifically, uranium-rich ores were discovered in the silicified fracture within the rock mass of the granite uranium deposit, while uranium was also found in the carbon-rich metamorphic rocks surrounding the mass. In addition, a large uranium deposit was found in the Mesozoic acidic volcanic rocks of the country's eastern region. Granite uranium deposits were discovered in the northwestern region, while uraniferous coal deposits and sandstone uranium deposits were found in the Cenozoic stratum in western Yunnan province. In sum, major progress was achieved in uranium prospecting in many locations throughout China. By the mid to late 1960s, the primary focus of uranium exploration had shifted from the northwestern to the southern region of the country.

In January 1964, China began to feed natural uranium into its first military uranium enrichment plant—the Lanzhou gaseous diffusion plant (GDP)—to produce highly enriched uranium (HEU). The Lanzhou plant provided HEU for China's first nuclear test in October 1964. In 1970, a second enrichment plant, the Heping GDP began operation.²¹

Boom Development for Military Purposes (1971–1985)

During the 1970s, China rapidly increased its exploration activities, primarily to secure uranium for the defense sector. Besides the two GDPs, uranium fuels were needed to supply China's two plutonium production reactors: the Jiuquan reactor which began operations in 1967 and reached full capacity in 1975, and the Guangyuan reactor, which operated in 1974.²²

In 1978, China's annual drilling efforts reached a peak of around 1,550 kilometers. However, as Beijing began to prioritize economic and political reforms initiated in 1978, China's uranium exploration effort began to gradually decline. In 1980, the Lanzhou GDP shifted to producing LEU for civilian purposes, and the Jiuquan reactor was closed in 1984.

Meanwhile, China's uranium industry began to shift its focus from military purposes to civilian nuclear energy. In 1978, Deng Xiaoping stated the state's intention to buy reactors from France, and after three years of negotiation the Daya Bay reactor deal (for the purchase of two French M310s) was signed in 1984. Also, China started a domestically designed reactor project—Qinshan-I—in 1983, with construction beginning in 1985. In 1983, Beijing adopted plans to greatly

²¹ See, e.g., Wang Zhaofu, “60 Years of New China's Nuclear Energy Development Key Events,” *Nuclear Energy*, No.5, 2009, <http://www.china-nea.cn/html/2009-11/4239.html> (accessed April 28, 2015).

²² Hui Zhang, “China's HEU and Plutonium Production and Stocks,” *Science & Global Security*, Vol. 19, No. 1 (2011), p. 68–89, <http://belfercenter.ksg.harvard.edu/files/huizhangSGS2011.pdf> (accessed April 28, 2015).

increase nuclear power development. However, this ambition was lowered to “modest” development in 1985 to reflect the relative costliness of nuclear power in comparison with coal-fired power.

From the 1970s to the mid-1980s, significant results were achieved in uranium exploration and the study of regional uranium mineralization patterns. Researchers also came to understand the geological conditions across the country that are conducive to mineralization much more thoroughly. Areas containing discovered granite uranium deposits further expanded, and significant progress was made in the search for volcanic rock uranium deposits. Unprecedented breakthroughs were achieved in the search for new kinds of deposits, and in particular exploration for high-grade ore yielded notable results. Chinese teams conducted basic evaluations of ore fields with relatively high concentrations of uranium and concentrated areas of mineralization that were considered to have long-term potential—these covered five provinces and more than ten mineralization zones. Moreover, means and technology for comprehensive geological prospecting had started to develop. A number of radiation detection methods, along with other geophysical and geochemical prospecting methods, were developed and widely employed.

Retraction and Adjustment (Late 1980s–2003)

As China deepened its “shift from military to civilian” in the nuclear industry during the late 1980s, domestic uranium exploration and mining activities began to shrink. During the period from 1986 to 2003, this trend continued mainly because the uranium requirements of the defense sector were significantly reduced, and there was no urgent demand from the country’s modest nuclear power program. In 1987, the Heping GDP stopped HEU production (the Lanzhou GDP had already ended HEU production in 1979). In 1991, China closed its second plutonium production reactor: the Guangyan reactor. Thus, since the early 1990s, there has been no uranium requirement for China’s weapons program.

Moreover, China had very modest plans for nuclear power during this period. In the 1990s, China operated only three PWRs with a total capacity of 2.3 GWe. In 1995, China decided to build eight reactors (with a total capacity of 6.9 GWe) over the 1996–2002 period, including two domestic PWRs (CNP-600) and two purchased from France, Canada and Russia each. Between 1995 and 2003, the government developed no further plans to build more reactors.

To shift its focus from military to civilian nuclear activities, in 1988, the Ministry of Nuclear Industry (MNI) was reorganized as the China National Nuclear Corporation (CNNC). The Bureau of Geology (BOG) of CNNC is responsible for the administration of uranium prospecting and exploration activities in China. As the result of reforms and restructuring within government organizations, since 1999 the BOG has been significantly transformed. To further reduce redundant labor, BOG transferred some of its geological teams and affiliated organizations or entities to local governments. The reformed BOG is composed of three geological teams, one airborne survey and remote sensing center, the Beijing Geological Research Institute for Nuclear Industry, six regional uranium geological research centers, and six regional uranium geological offices. The BOG will continue to undertake uranium exploration in China, and transferred entities will no longer take part in those activities except when under contract with the BOG. After the reorganization, the total staff of the BOG was reduced to about 5,500, from around 45,000 in 1984.

In the 1990s, as the central government sharply reduced its investment in uranium exploration activities, the BOG concentrated its exploration efforts on sandstone-type deposits amenable to *in situ* leaching techniques in northern and northwest China. This shift led to a substantial reduction in exploration of other deposit types including granitic, carbonaceous-siliceous-pelitic, and volcanic deposits located mainly in southern China. In 1999, drilling activities reached their lowest point of about 24 kilometers per year. During the 1990s, the average annual drilling distance was maintained at only about 40 kilometers—nearly 40 times less than at the peak of activity (in 1978, when 1,550 kilometers were drilled).

However, despite the fact that uranium reconnaissance work was at an historical low, some advances were made in the research and work on mineralization patterns. For instance, a series of national and regional geological mappings of uranium deposits, as well as some documentary work (i.e., the work of recording and finalizing uranium reconnaissance experiences), were completed in that period.

Revival and Acceleration (2004–Present)

Since 2004, China's state policy guiding the development of nuclear power changed the officially endorsed pace of growth from "moderate development" to "active development." To meet expectations of a rapid increase in uranium requirements, uranium prospecting and exploration in China accelerated greatly, both in terms of expenditures incurred and meters drilled. In 2003, total expenditures for domestic uranium exploration (exclusively those incurred by the government) were \$7.6 million (in 2005 dollars) and the total distance drilled was about 130 kilometers. In 2012, total expenditures for domestic uranium exploration were \$131 million (including government expenditures of \$85 million and industry expenditures of \$35 million) and the total distance drilled was 922.6 kilometers.²³ Consequently, China's identified uranium resources increased to 265,500 tU in 2012 from 85,000 tU in 2004—a more than three-fold increase.

To secure supplies of uranium fuel for its fast-expanding nuclear power plants, the central government has taken a number of measures to intensify uranium exploration and mining in China, including increasing government investments and allowing involvement by organizations other than CNNC. Also, the government has endorsed a strategy of "two markets and two resources," referring to overseas purchase and production (see detailed discussions in Section IV). In 2006, the State Council issued its first official policy on the government's role in managing national uranium resources: "strengthening uranium exploration, speeding up its new exploration." In 2008, China issued a policy to encourage new investors to invest in uranium exploration and mining based on the principle of "whoever invests, benefits."²⁴

As the government emphasizes the importance of uranium fuel supplies and increases its investments in uranium exploration, China has continued and markedly intensified uranium prospecting and exploration in its northern region, especially for uranium deposits suitable for *in situ* leaching. As a result, several large- and medium-scale deposits have been established that are

²³ OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*, OECD (Paris, France and Vienna, Austria: OECD-NEA 2014) <http://www.oecd-nea.org/ndd/pubs/2014/7209-uranium-2014.pdf> (accessed April 28, 2015).

²⁴ Ma Zhe and Zhu Rui, "Speeding up construction of large base of uranium mines," *China Energy News*, January 14, 2013, http://paper.people.com.cn/zgnyb/html/2013-01/14/content_1185017.htm (accessed May 6, 2015).

amenable to mine design and mining. Also, great breakthroughs were made in the sandstone uranium deposits in the Ordos and Erenhot basins in Inner Mongolia, including the discovery of several large-scale uranium deposits, particularly the large Daying deposit which was discovered in the Erdos basin in 2012.²⁵ As a consequence of these discoveries in northern China, the country's identified uranium resources have significantly increased since the mid-2000s.

Meanwhile, since the mid-2000s, uranium prospecting and exploration work in southern China have resumed, leading to the discovery of vein-type uranium deposits related to volcanic rock and granite in several provinces.

Characteristics of China's Uranium Deposits

China's uranium resources are broadly distributed across the country²⁶—the over 350 uranium deposits discovered thus far are situated in 23 different provinces and autonomous regions.²⁷ The medium- and large-sized uranium deposits account for about 27% of the total deposits, and 77% of the total known uranium resources.²⁸ Moreover, many uranium deposits are located in concentrations which facilitate mining work.

As a result of China's complex tectonic background, uranium deposits in the country are varied both in kind and cause of formation. More than ten types of uranium resources have been discovered in China. As of 2012, 35% of resources were in sandstone deposits found mainly in the north and northwest, 28% in granite deposits in central and southeast China, 21% in volcanic deposits in the southeast, 10% in black shale in the southeast, and 6% in other types.²⁹ Most known resources are at a depth of less than 500 meters. It should be noted that because significant amounts of sandstone deposits in the north and northwest have been identified over the last decade, this type of uranium deposit is now the dominant constituent of the national known resource, which is a change from 1996 when uranium in granite rocks was the largest component (see Table 3.1).

A majority of the uranium ores discovered in China are of a grade of between 0.1% and 0.3%. Those with a grade level higher than 0.3% constitute only a few percent of the total; whereas

²⁵ Ministry of Land and Resources, "Achieving a Historic Breakthrough on Nuclear Power, Oil and Gas Exploration," *Xinhua Net*, September 16, 2014. <http://news.bjx.com.cn/html/20140916/546828.shtml>. (accessed May 6, 2015).

²⁶ Following IAEA practice, we refer to both known and readily producible deposits of uranium and speculative potential uranium as "resources" of various types. In much of the resource economics literature, a distinction is made between "reserves," that are those amounts that have been identified with reasonable confidence and can be produced profitably with current technology at current prices, and "resources" which refers to the broader set of all deposits of that material that are likely to exist and to be recoverable at some point in the future. "Reserves" in that sense correspond roughly to the IAEA's category of "reasonably assured resources" recoverable in the range of current prices.

²⁷ Zhang Jindai, Li Youliang, and Jian Xiaofei, "Situation and Development Prospects of Uranium Resources Exploration in China," *China Engineering Science*, Vol. 10, No. 1 (2008), p. 54–59; Zhang Jindai, "China's Uranium Potential and Prospects," *China Nuclear Industry*, No.2 (2008), p. 18–21.

²⁸ Ma and Zhu, "Speeding up Construction of Large Base of Uranium Mines."

²⁹ Li Ziyang, "Uranium Resource Potential and Recent Major Exploration Progress in China," (presented to 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 (accessed April 28, 2015).

those with a grade level lower than 0.1% constitute about one-third. The thickness of most ore bodies is between 1 and 5 meters.³⁰

Many kinds of minerals are recovered through uranium mining as by-products. So far, the elements recovered alongside uranium as by-products include thorium, molybdenum, germanium, vanadium, yttrium, and rare earth metals, but at present the level of comprehensive utilization of these by-products remains comparatively low. Representative of such composite deposits are the germanium-uranium deposit in Lincang city, Yunnan province, and the uranium-molybdenum deposit in Zhangmajing in Guyuan county, Hebei province. In particular, the germanium resources of the germanium-uranium deposit in Lincang city are unusually large.

Over the past several decades, uranium deposits in China have been generally characterized by Chinese experts as “small but many, low-grade but usable, dispersed but relatively concentrated (production)” —in other words, it is evident that China has a large number of uranium deposits with ore of usable quality, and relatively concentrated uranium production.³¹ However, this situation has been changing recently as more large-scale deposits are discovered.

China’s Known Uranium Resources

According to *Uranium 2014: Resources, Production, and Demand* (also known as the “Red Book”) report, as of January 1, 2013, China’s identified conventional uranium resources—reasonably assured resources (RAR) and inferred resources (IR)—totaled 265,500 tU as listed in Table 3.2, and distributed mainly within 11 provinces (see Table 3.3).

However, China’s uranium resources are expected to continue increasing in the future. As discussed in the following sections, an identified uranium resource is a dynamic economic concept. Its size will depend on a number of factors, including technological advances, engineering fea-

Table 3.1: China’s Known Uranium Resources by Host Rock Lithology

Host Rock	Shares of Total 1996 Resources (%) ^A	Shares of Total 2012 Resources (%) ^B
Sandstone	21	35
Granite	38	28
Volcanic	20	21
Carboneous-siliceous-pelitic rock	16	10
Others	5	6

^A Resources in 1996 were 64 ktU. See OECD-NEA and IAEA, *Uranium 1997: Resources, Production and Demand*, (OECD-NEA: Paris, France and Vienna, Austria:1997), <http://www.oecd-nea.org/tools/publication?query=red+book&div=&lang=&period=100y&sort=title&filter=1> (accessed April 28, 2015).

^B According to Red Book 2014, resources in 2012 were 265.5 ktU. See Li Ziyang, “Uranium Resource Potential and Recent Major Exploration Progress in China.”

³⁰ Guo Lian and Chen WenLing, ed. *Research on China Bulk Mineral Sources and Coping Strategies*, (Social Science Academic Press: Beijing, China, 2014) p. 301–302.

³¹ Zhang, et al., “Situation and Development Prospect of Uranium Resources Exploration in China.”

sibility, exploration expenditures, uranium prices, and limitations of ore grade. For example, as expenditures on uranium exploration are increased, more resources are identified. As technology for exploration and mining improves, previously non-feasible lower-grade ores become usable, thus significantly increasing minable uranium resources.

Indeed, China is finding that it has much more domestic uranium than it once thought. After 2004, when the central government decided to pursue “active development” of nuclear power, the country increased its uranium exploration activities and developed more advanced techniques. As a result, China’s uranium resources have increased almost three-fold since 2004 (see Figure 3.2).³² In addition, China estimates it has a uranium potential of over 2,000 ktU (see details in following discussions).

Table 3.2: China’s Identified Resources (RAR and IR)

	<USD 40/kgU	<USD 80/kgU	<USD 130/kgU	<USD 260/kgU
RAR: <i>In situ</i>/Recoverable	69,000/51,800	125,000/93,800	160,000/120,000	NA/120,000
IR: <i>In situ</i>/Recoverable	18,500/13,900	73,000/54,800	105,500/79,100	NA/79,100
Identified Resources: <i>In situ</i>/Recoverable	87,500/65,700	198,000/148,600	265,500/199,100	NA/199,100

Note: *In situ* and recoverable resources as of January 1, 2013, tonnes of Uranium. *Recoverable resources* RAR and IR estimates are expressed in terms of recoverable tonnes of uranium, i.e., quantities of uranium recoverable from mineable ore, as opposed to quantities contained in mineable ore, or quantities in situ, i.e., not taking into account mining and milling losses. For China’s case, the recovery factor is estimated around 75%. See details in Red Book 2014.

Source: Based on Red Book series from 1997 to 2011: OECD-NEA and IAEA, *Uranium* [various years]: *Resources, Production, and Demand*.

Figures 3.2 and 3.3 show that China’s identified uranium resources have been increasing rapidly due to increasing exploration expenditures and drilling since 2004. As shown in Figure 3.4, China has been discovering new uranium resources each year in multiples of the amounts it consumes. This trend is expected to continue in the near future.

³² Based on Red Book series from 1997 to 2011: OECD-NEA and IAEA, *Uranium* [various years]: *Resources, Production and Demand*.

Table 3.3: Regional Distribution of Chinese Identified Uranium Resources

Province	Region	Identified Uranium (tU)
Jiangxi	Xiangshan	32,000
	Ganzhou	12,000
	Taoshan	12,500
Guangdong	Xiazhuang	15,000
	Zhuguangnanbu	25,000
	Heyuan	4,000
Hunan	Lujing	9,000
Guangxi	Ziyuan	11,000
Xinjiang	Yili	33,000
	Tuha	10,000
Inner Mongolia	Erdos	35,000
	Erlian	40,000
	Tongliao	4,000
Hebei	Qinglong	8,000
Yunnan	Tengchong	6,000
Shanxi	Lantian	2,000
Zhejiang	Dazhou	5,000
Liaoning	Benxi	2,000
Total Identified Uranium Resources		265,500

Note: *In situ* resources as of January 1, 2013, tonnes of Uranium.

Source: Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

As China continues its exploration efforts, how much more uranium could be discovered? As shown in Figure 3.2, the cumulative discoveries are 185.5 kt U during the period between 2004 and 2012; and the cumulative expenditures during the period are around \$590 million (in 2015 dollars). This means China had an average expenditure rate of \$74 million/year thus an average growth rate at 22.6 ktU/ year during the period. Thus, the cost of discovery is around \$3.2/kg U for the period. To attain a simple projection for the period between 2013 and 2050, we assume China continues to spend on exploration at the same average rate and at the average discovery cost of \$3.2/kg U as it did during the period between 2004 and 2012, then China could identify a total uranium of around 1124 ktU, about half its predicted uranium potential of 2,000 ktU. It should be noted that the predicted uranium potential would also be increased as exploration and prospecting efforts further increased. Hence, if China keeps finding uranium at the same annual rate as it did during the period from 2004 to 2012 (no increase in rate from greater expenditures), it would find enough uranium to meet all of China's needs even in the high-growth scenario (a million tons by 2050) from domestic resources alone.

Figure 3.2: China's Identified Uranium Resources and Exploration Expenditures

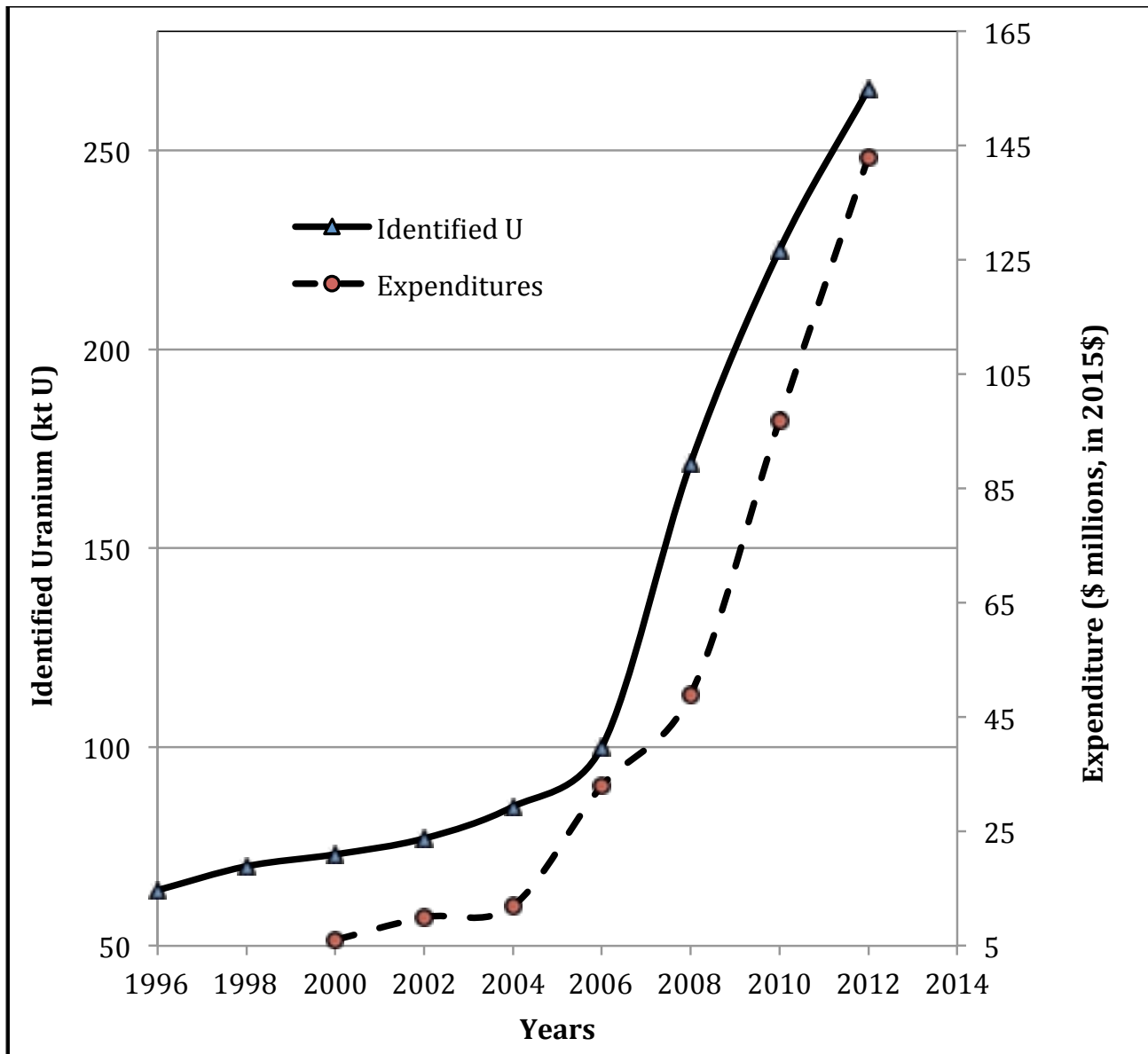


Figure 3.3: China's Identified Uranium Resources and Exploration Drilling

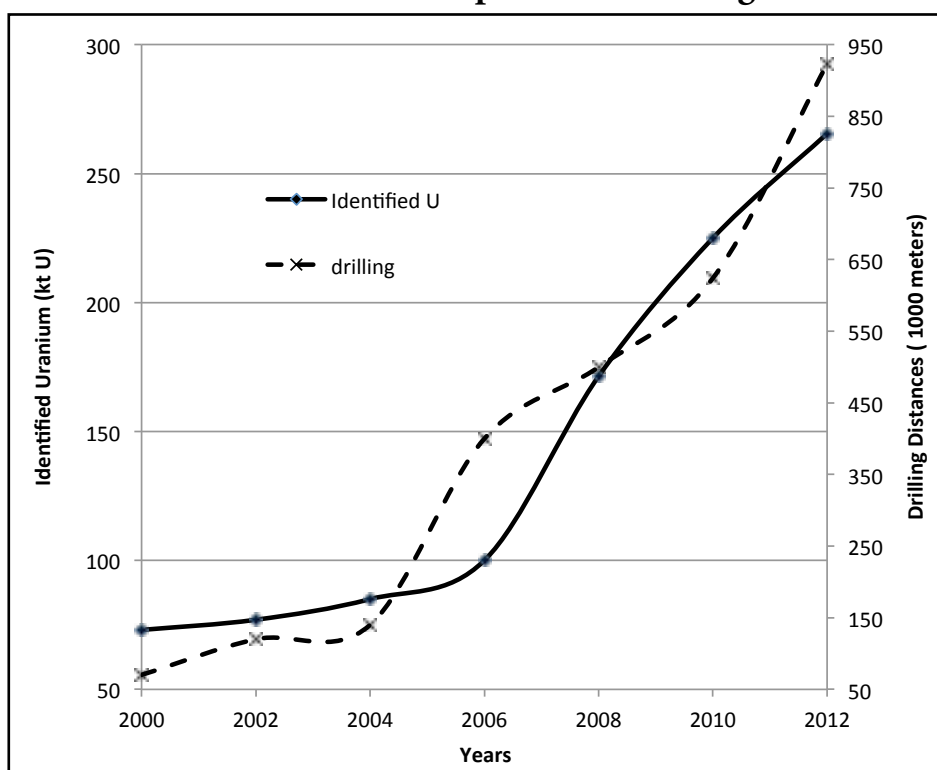
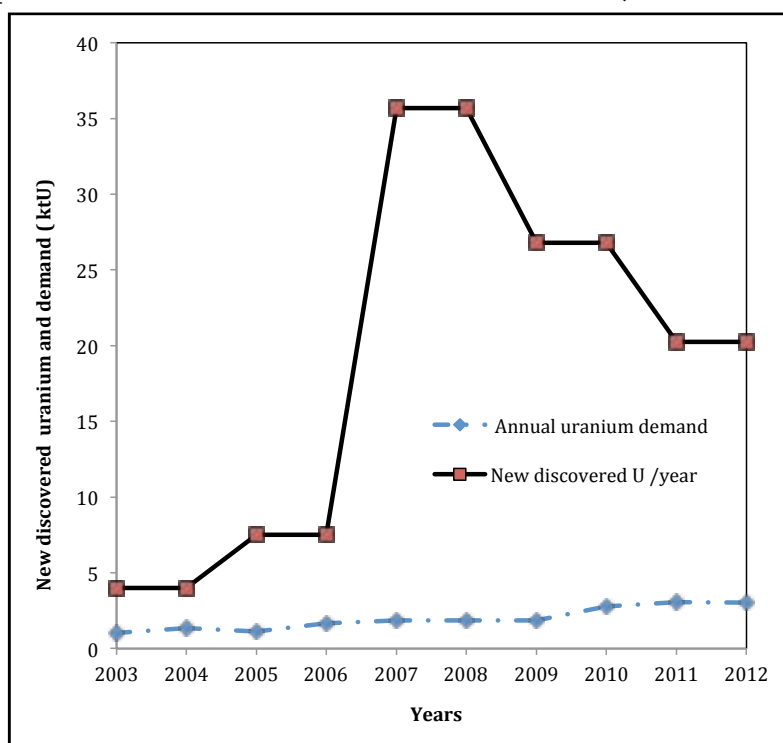


Figure 3.4: China's Newly Discovered Uranium Resources per Year and Annual Uranium Demand (2003–2012)

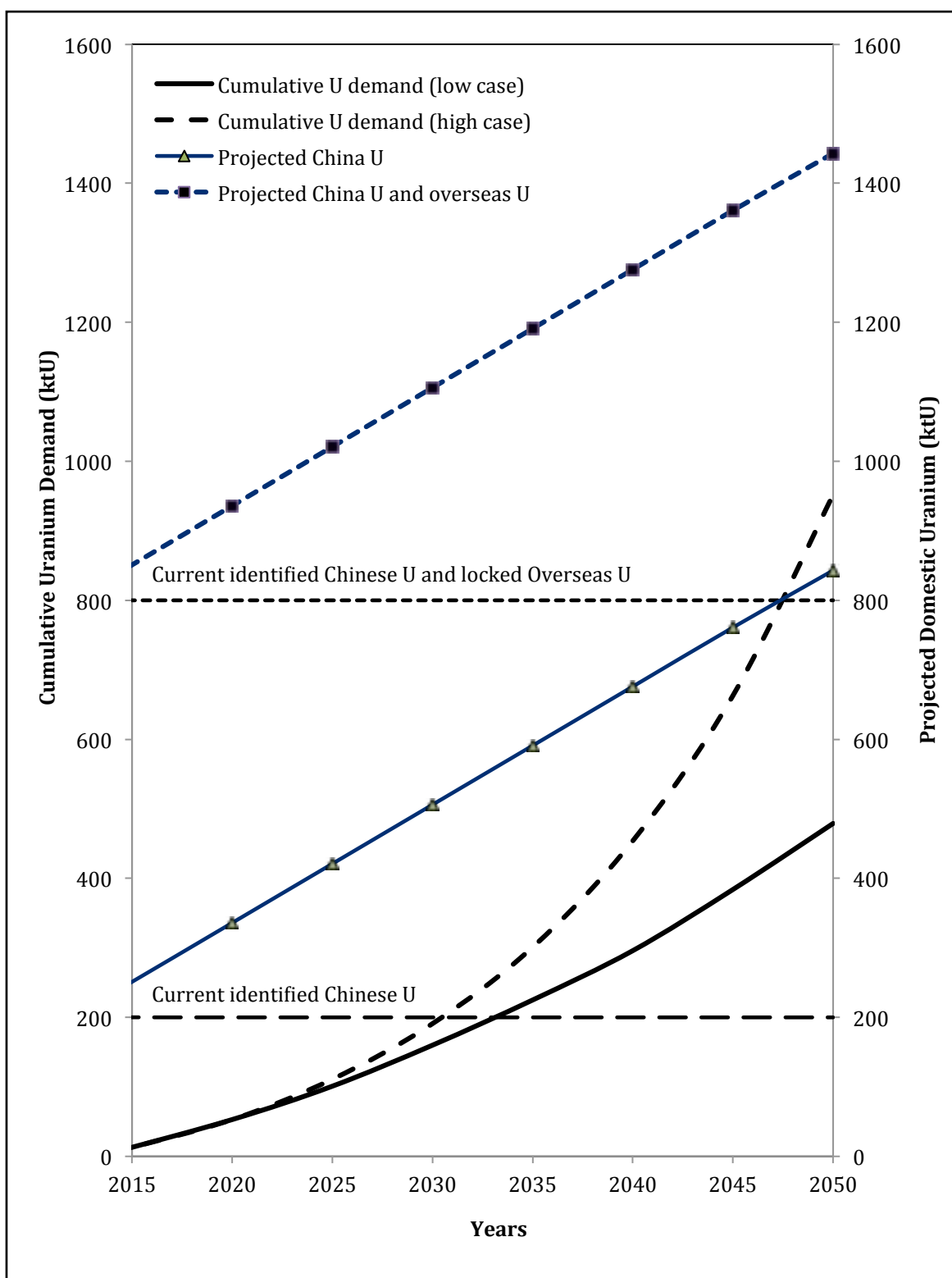


Finally, can China's known uranium resources meet the demands of its plans for nuclear power development? Figure 3.5, based on Table 2.3, shows the clear relationship between demand and supply of uranium. There are around 200 ktU recoverable at a cost of less than \$130/kgU (see Table 3.2), which would be sufficient to support even the high-growth scenario through 2030, i.e., a total cumulative uranium demand of around 191 ktU for a generation capacity of 115 GWe. In addition, China has already locked in supplies of overseas uranium of around 230 ktU through trade and foreign supply of LEU (see Table 4.6 in Section IV). Thus, a total of around 430 ktU available at relatively low price would be sufficient to meet the country's ambitious nuclear plan up to 2040.

However, if China continues to spend on exploration at the same average rate and at the average discovery cost of \$3.2/kg U as the period between 2004 and 2012 (as discussed before), then China could identify a total uranium of around 1,124 ktU (*in situ* resources) by 2050 (i.e., around 843 kt recoverable uranium resources), close to the uranium demand even under the high-growth scenario (i.e., 950 ktU). Thus, combining locked overseas uranium (230 ktU) through trade and foreign supply of LEU, China would have around 1,000 ktU by 2050, sufficient enough to meet its needs.

Further, over 400 ktU will be secured through overseas exploration and mining and can be added to the national stockpiles (see details in Table 4.6 of Section IV). Thus, even without those new domestic discoveries, a total supply of 830 ktU (i.e., 200 ktU of currently identified domestic uranium and 630 ktU of overseas uranium) will be available to meet a projected demand of between 380 ktU and 660 ktU for a nuclear industry with a capacity of 118 to 343 GWe through 2045. However, demand might not be met through 2050, with projected capacity at 400 GWe requiring cumulative total uranium about 950 ktU. However, the gap of 120 ktU would easily be filled by continuing increases in new domestic discoveries and expansion of overseas mining and imports. Consequently, China's domestic and overseas uranium would be sufficient to supply its nuclear power development even under the high-growth scenario beyond 2050.

Figure 3.5: China's Projected Cumulative Uranium Demand (2015–2050)



Uranium Production in China

Currently, China operates six production centers (see Table 3.4), in Fuzhou and Chongyi in Jiangxi province, Yining in Xinjiang Autonomous Region, Lantian in Shaanxi province, Benxi in Liaoning province in northeastern China, and Shaoguan in Guangdong province.³³ Total normal production capacity is about 1450 tU per year and plans exist to expand capacity to 3250 tU per year. While several of the existing centers are being expanded, China is also conducting pilot tests and feasibility studies at certain previously undeveloped sandstone uranium deposits with abundant resources that are suitable for *in situ* leach (ISL) mining, such as the deposits in Erduos and Erlan. All six existing centers are operated by CNNC—a 100% state-owned company and the only current supplier of domestic uranium. However, this situation could change. China General Nuclear Power Group (CGN), also a state owned company, which has been energetically involved in the acquisition of uranium assets abroad alongside CNNC, announced in May 2011 that it would develop two 500 tU/year mines in Xinjiang, beginning in 2013.

**Table 3.4 : Existing Uranium Production Centers in China
(as of January 2013)**

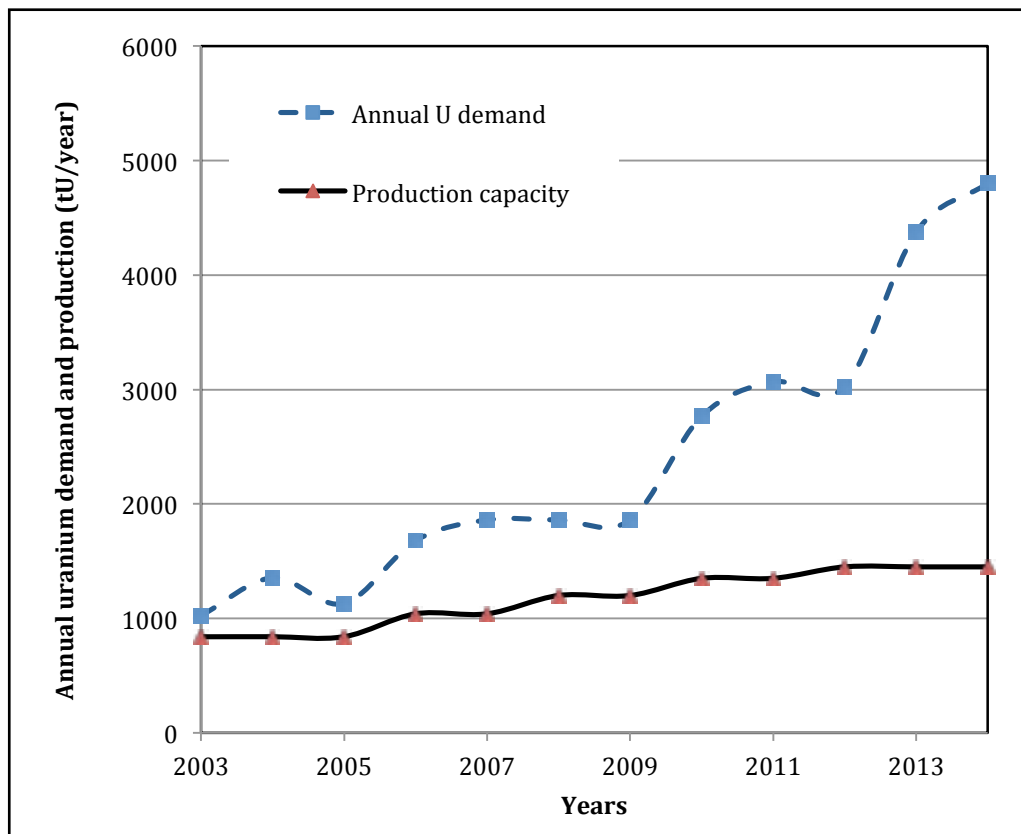
Name/ Province	Started	Source of Ore	Mining/ Processing	Normal capacity (tU/year)	Expansion Plans (tU/year)
Fuzhou/ Jiangxi	1966	Volcanic	Underground/mill	350	500
Chongyi/ Jiangxi	1979	Granite	Underground/ heap leach	200	300
Yining/ Xinjiang	1993	Sandstone	In-site leach/ISL	380	500
Lantian/ Shaanxi	1993	Granite	Underground/ heap leach	100	NA
Benxi 1/ Liaoning	1996	Benxi Granite deposit	Underground/ heap leach	120	NA
Benxi 2/ Liaoning	2007	Qinglong Volcanic deposit	Underground/ heap leach	100	200
Shaoguan/ Guangdong	2008	Granite	Underground/ heap leach	200	300

Source: Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*; World Nuclear Association, “China’s Nuclear Fuel Cycle.”

³³ Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

To meet increased uranium demand from power plants, China has been increasing its uranium production since 2005. As shown in Figure 3.6, however, since that year China's annual uranium requirements have been increasing faster than its domestic production capacity. In recent years, domestically produced uranium has only met around one-third of annual uranium requirements. While China plans to expand its normal production capacity from about 1,450 tU per year to 3,250 tU per year, it is still not able to meet its demand in the near future. It is expected that China's annual uranium requirements will increase to about 12 ktU in 2020 from 4.8 ktU in 2014. Given the big gap between demand and domestic supply of uranium, some Chinese experts argue that China's lack of uranium will constrain development of its nuclear power industry. However, uranium production capacity is not the same thing as supply capacity from uranium resources. In fact, as was shown in Figure 3.4, total new discoveries of uranium have increased between 2004 and 2012 at an average rate of 23 ktU/year, several times more than annual requirement increases.

Figure 3.6 China's Annual Uranium Requirements and Production Capacity



Source: China's uranium production capacity is based on Red Book series from 2003 to 2014. The estimates of annual uranium demand is discussed in Section III. OECD-NEA and IAEA, *Uranium* [various years]: *Resources, Production, and Demand*.

China could increase uranium production more rapidly than it has in the past. However, given that a majority of the uranium ores discovered in China are of poor quality and ores of more than 0.3% concentration are only a few percent of discovered ores, Chinese ores will be costly to mine by comparison, say, to those in Canada, (which sometimes reach 5–20% U concentrations). Hence, China has instead taken advantage of low international uranium prices (see further details in following sections on China’s acquisitions of foreign uranium).

Analysis of the Situation and Prospects for China’s Uranium Resources

From 1985 to 1991, Chinese uranium geologists conducted work to predict the country’s total uranium potential based on appraisal and prediction methods. Based on contemporary capabilities, they predicted that uranium potential at the major metallogenic belts and regions would be multiples more than then-known resources and that the total uranium potential would be around 1.7 million tonnes.³⁴ However, due to very limited budgets, more detailed work was not done.

Driven by increasing uranium demand for the active nuclear development plan, the government organized in 2010 a new round of predictions of total uranium potential. Notably, this new round of work considers new areas, including those in northern China with huge uranium potential in sandstone, formerly untouched areas (e.g., Qinghai and Tibet), and deeper zones between 500–1000 meters (instead of focusing solely on currently developed zones at less than 500 meters in depth). Based on uranium metallogeny, new models, and exploration data from the past several decades, recent predictions indicate that China could have over 2 million tonnes of potential uranium resources.³⁵

There are several major reasons to support predictions of a huge uranium potential:

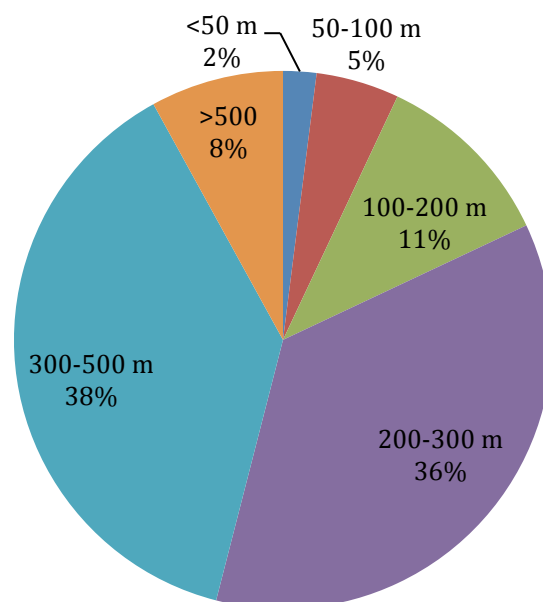
First, China still has huge areas awaiting exploration. Areas that have been surveyed at a high level of detail (i.e., at a scale greater than $1:5 \times 10^4$) extend to only 100,000 square kilometers and include mainly known uranium ore fields or deposits and their surroundings. Areas that have been surveyed to a lesser, but still relatively high, level of detail (of a scale of between $1:5 \times 10^4$ and $1:10 \times 10^4$) include about 1 million square kilometers and cover target regions of uranium metallogenic belts and regions. However, a total area of around 6.2 million square kilometers (about two-thirds of China’s total area), which Chinese experts believe represent a huge uranium potential, have only seen very low levels of work or even no attention at all.³⁶ In fact, in the last several years, China has identified favorable areas in regions including the Erlian basin of the Inner Mongolia Autonomous Region, the Tarim and Junggar basins in the Xinjiang Autonomous Region, and the Songliao basin in northeastern China.

³⁴ See <http://info.metal.hc360.com/2008/06/19110255011.shtml> (in Chinese).

³⁵ See, e.g., China Academy of Engineering, *China’s Medium- and Long-Term Energy Development Strategy (2030, 2050)* (in Chinese); Guo Lian and Chen WenLing, ed. “Research on China Bulk Mineral Sources and Coping Strategies, (in Chinese);” Li Ziyang, “Uranium Resource Potential and Recent Major Exploration Progress in China.”

³⁶ Lei Guangyuan, “China’s Uranium Potential and Prospective,” (in Chinese) July 14, 2010, see website at <http://www.chinavalue.net/Biz/Article/2010-7-14/191939.html>; also Li Ziyang, “Uranium Resource Potential and Recent Major Exploration Progress in China.”

Figure 3.7: Depth Distribution of Known Uranium Resources



Second, a big resource potential could lie in depth. Most of China's current identified resources (over 90%) are located at a depth of less than 500 meters (see Figure 3.7). However, exploration experience in other nations, including Russia, South Africa, Canada, and Germany, has shown that uranium resources can be located in much deeper areas than 500 meters (even greater than 1000 meters in depth). According to analysis based on mineralization theory, the vertical depth of a hydrothermal metallogenesis system can reach 4 to 5 kilometers. In fact, China has recently discovered uranium resources at depths of between 500 and 1,000 meters in southern China, such as: the volcanic rock uranium ore field in Xiangshan, Jiangxi province, which has known resources at depths of between 700 and 1,000 meters; granite-related uranium deposits in northern Guangdong province with uranium resources at depths of between 700 and 1,000 meters.³⁷ Chinese experts expect more uranium resources will be discovered beyond depths of 500 or even 1,000 meters.

Third, China has favorable geological conditions for uranium mineralization. Based on scientific evaluations, Chinese experts in uranium geology believe that the geological context of uranium mineralization in China exhibits major favorable factors, including:

- East China's important position on the uranium metallogenic belt of the Pacific Rim.³⁸ Many Chinese uranium deposits are located near the giant western Pacific uranium metallogenetic belt. These are the deposits in South China (Jiangxi, Guangdong, Hunan, Guangxi, and Zhejiang) and North China (Hebei, Inner Mongolia, and Liaoning) with acidic intrusive rocks and volcanic rocks. Chinese experts expect to discover more uranium resources in these regions.

³⁷ Yunsheng Bai, "China's Uranium Resources Situation" (presented at Harvard-Peking Workshop on Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011). Also, see Li Ziyang, "Uranium Resource Potential and Recent Major Exploration Progress in China."

³⁸ Lei Guangyuan, *Potential and Prospects of China's Uranium Resources* (in Chinese), *Chinavalue.net*, July 14, 2010. <http://www.chinavalue.net/Biz/Article/2010-7-14/191939.html> (accessed May 6, 2015).

- North China's important position on the Eurasian uranium metallogenic belt. Some uranium deposits (including the sandstone rocks in Xinjiang and Inner Mongolia, and the acidic intrusive rocks and volcanic rocks in Gansu and Shannxi) are in this belt. Given that other countries in this belt, such as the Central Asian nations of Kazakhstan and Uzbekistan, host many large- or super-large uranium deposits, China can expect to have more uranium resources in its regions as well.
- The dominance of uranium resources mineralized during the Meso-Cenozoic era among the resources discovered thus far in China, and the very small proportion of discovered uranium resources mineralized during the Paleozoic era and the Precambrian era. This contrasts surprisingly with the fact that many other minerals mineralize predominantly during the Precambrian era (particularly the Proterozoic eon) and the Paleozoic era, and that the Precambrian era was a significant geological time for uranium mineralization in many major uranium-producing countries (e.g., Australia and Canada). Thus, many Chinese experts expect that there is potential to discover more uranium mineralized during those two periods as uranium reconnaissance and exploration work moves forward.
- Likelihood of large overlaps with other polymetallic mineralization areas, as concluded based on general mineralization experience in China.³⁹ However, uranium geology work has yet to be conducted in many of these polymetallic mineralization areas due to unfavorable natural conditions. While some very low-level uranium work has been conducted, these areas have yet to be developed into uranium mineralization belts. However, polymetallic mineralization areas could have great uranium potential.

Eventually, given the significant increase in China's known uranium resources over the last several years and the new estimates of a huge uranium potential, Chinese officials and uranium geology experts moved recently from referring to China as a "uranium-poor" country to a "uranium-rich" country.⁴⁰

Finally, Chinese experts have addressed the likelihood that China also has a huge amount of unconventional uranium resources (UUR) (which refers to ore grades of between 0.01%-0.03%).⁴¹ In 2009, China initiated a research project on the "investigation and evaluation of UUR in China."⁴² In particular, uranium-bearing phosphorite holds great potential. Uranium content is generally high in phosphate deposits and abundant phosphorous resources of nearly 20 billion tonnes are located in China, which would have about 1 million tonnes of uranium in phosphate rock.⁴³ However, it is not economical to extract except as a co-product at existing phosphate operations.

³⁹ Zhang Jindai, Li Youliang, and Jian Xiaofei, "Situation and Development Prospect of Uranium Resources Exploration in China."

⁴⁰ Communications with Chinese nuclear experts, July, 2014.

⁴¹ Qin Mingkuan, "Current Progresses and Prospects on Unconventional Uranium Resources (UUR) of China," (presented in Vienna, Austria, November 4, 2009) http://www.iaea.org/OurWork/ST/NE/NEFW/documents/RawMaterials/TM_Vienna2009/presentations/9_QIN-CHINA.pdf (accessed April 28, 2015).

⁴² Mingkuan, "Current Progresses and Prospects on Unconventional Uranium Resources (UUR) of China."

⁴³ As a conservative estimate, assuming uranium grades around 50 weight parts per million in phosphate rock (can be as high as 200 wppm).

IV: China's Pursuit of Uranium Abroad

To meet the increasing uranium requirements of its plans for the development of nuclear power, in the mid-2000s the central government adopted the policy of “Facing Two Markets and Using Two Kinds of Resources,” a uranium resource strategy of combining “domestic production, overseas exploitation, and the world trade of uranium” to secure uranium supplies. Since then, China’s nuclear industry has been active not only in purchasing foreign uranium products, but also participating in overseas exploration and mining. To secure the resources demanded, China has used long-term agreements and diversified risk by using multiple supply sources; this policy has ensured uranium supply for the development of nuclear power in China.

In practice, Chinese nuclear power operators follow the “Three One-Thirds” rule—one-third from domestic supply, one-third from mining abroad, and another third from direct international trade—to ensure a stable supply in the long term.⁴⁴ Some experts believe that China plans to reach a target of 40–50% from domestic supply. As shown in Figure 3.6, in recent years, domestic uranium production has been equal to one-third of national uranium needs. CNNC, so far the sole owner of uranium production centers in China, plans to increase annual output from 1,450 tonnes (in 2012) to between 4,000 and 5,000 tonnes by 2020⁴⁵ which would be less than half of national demand (as shown in Table 2.2, an annual uranium requirements could reach an estimated 12,000 tonnes by 2020).

The major players involved in acquisition of foreign uranium include CNNC and CGN; both are state-owned companies. On December 28, 2006, CNNC established a wholly-owned subsidiary, China Nuclear International Uranium Corporation (henceforth referred to as SinoU), responsible for CNNC’s foreign uranium-related activities, including exploration, resource evaluation, construction of and investment in mining facilities, and milling, production, and management of natural uranium. SinoU has been actively exploring for and mining uranium in several countries, such as Niger, Namibia, Zimbabwe, and Mongolia. A different CNNC subsidiary, China Nuclear Energy Industry Corporation (CNEIC), is responsible for acquisition of uranium through international trade. It has been involved in the international nuclear fuel trade business for more than 30 years and has established trade relations with uranium-producing countries such as Kazakhstan, Canada, Australia, and Namibia. At the end of 2009, the head of CNNC announced that the company had secured over 200 ktU in foreign resources and imported 6–8 ktU each year through international trade.⁴⁶

Meanwhile, in 2006, a CGN subsidiary, CGN Uranium Resources Co. Ltd. (CGN-URC) was set up and broke CNNC’s monopoly in access to foreign uranium resources (CNNC’s monopoly on

⁴⁴ Wei Qiyao, “CGN’s Global Uranium Investment” (presented in Istanbul, Turkey, June 9–11, 2013). Also see, Liu Yiyu, “CNNC Begins Trials at Uranium Mine in Niger,” *China Daily*, March 24, 2011, http://www.chinadaily.com.cn/business/2011-03/24/content_12220006.htm (accessed April 28, 2015).

⁴⁵ See, e.g., Liu Yiyu, “CNNC Begins Trials at Uranium Mine in Niger.”

⁴⁶ See, e.g., Duan Xinxin, “Nuclear Power: ‘Power China’ Target is Coming,” *China Energy News* (in Chinese), December 28, 2009. Yu Jianfeng, vice president of CNNC, told *China Energy News* that CNNC had locked over 200 ktU in foreign resources and imported 6–8 ktU each year through international trade, http://paper.people.com.cn/zgnyb/html/2009-12/28/content_413984.htm (accessed April 28, 2015).

domestic uranium resources persists for now). CGN-URC is responsible not only for uranium exploration and mining abroad, but also for international trade in uranium. It has been actively exploring for and mining uranium in Kazakhstan, Namibia, Australia, and Uzbekistan. It has also established natural uranium trade relations with Kazakhstan, Uzbekistan, Canada, and Australia. In 2013, the head of CGN stated that the firm had secured approximately 308,000 tonnes of overseas natural uranium resources by the end of 2012, and that more would be acquired.⁴⁷ In addition, it has secured an overseas uranium supply of 79 ktU through international trading.⁴⁸

Chinese Purchases of Uranium Worldwide

To inform our estimate of the supply and demand for uranium for China's nuclear power development from 2014 to 2050 (to be referred to as the "plan period"), we take 2014 as the base year and examine how much uranium from those international trading deals (that can contribute to the "plan period") has been made available. Of course, Chinese companies could sign further deals before 2050 if they so desired, given that they have established good relations worldwide with major uranium suppliers.

Uranium Purchases by CNNC

On June 24, 2010, CNEIC signed a long-term contract with Canada's Cameco to import 10,000 tonnes of uranium over a ten-year period.⁴⁹ Assuming 3 ktU had been imported between 2011 and 2013 (based on an assumed average import rate of 1 ktU/year), there are still 7 ktU to be imported and made available for use during the plan period.

On February 21, 2011, CNEIC signed a long-term uranium supply contract with Kazatomprom for a total of 30 ktU, to be supplied from 2011 to 2020.⁵⁰ Similarly, based on an assumed average import rate of 3ktU/year, 9 ktU had been imported before 2014. Thus, 21 ktU would be available for the plan period.

In addition, early in 2006, China signed two important agreements with Australia that related to uranium sales and nuclear cooperation. The Nuclear Transfer Agreement permits China to use Australian uranium in specified installations, while the Nuclear Cooperation Agreement allows Chinese entities to search Australia for uranium. Both CNNC and CGN have purchased Australian uranium. Altogether, China imports around 500 tonnes of uranium each year from Australia. However, it is not clear if the deal is secured by a long term contract. Assuming a supply rate of 0.5 ktU/year is maintained between 2014 and 2050, and CNNC shares half of the supply, then a total of 9 ktU would be available during the plan period.

⁴⁷ See, e.g., He Yu, the president of the board of CGPNC, "Uranium resources for China's NNP Can Meet the Needs of its Nuclear Power Development," *Xinhua News* (in Chinese), March 13, 2013, <http://www.cec.org.cn/redianxinwen/lianghuihuanyuan/dianlirenwu/2013-03-13/98671.html> (accessed May 3, 2015).

⁴⁸ Statement on CGN home page (in Chinese), <http://www.cgnpc.com.cn/n1381/n1419/n1421/index.html> (accessed May 17, 2015).

⁴⁹ See, e.g., Zhang Yi, "Recent Development of Uranium Industry in China" (presented to workshop on Recent Developments in Evaluation of Uranium And Thorium Resources and Possibilities for Application of UNFC, Lisbon, Portugal, October 15–18, 2012), http://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/ws_IAEA_CYTED_UNECE_Oct12_Lisbon/21_Zhang.pdf (accessed April 28, 2015).

⁵⁰ See, e.g., Zhang Yi, "Recent Development of Uranium Industry in China."

Based on CNNC's claim that it has secured imports of 6–8 ktU per year through international trade, it is reasonable to assume that other purchase deals, whether short- or long-term have been signed. However, there is no further information available that can be used to figure out the details. If those deals above account for 4.3 ktU/year, there could be other deals contributing a total of 1.7–3.7 ktU/year. Over a ten-year supply period, that would be around 27 ktU.

Consequently, at minimum CNNC could make available a total of 64 ktU for the period between 2014 and 2050.

Uranium Purchases by CGN

Since 2006, CGN has also been actively involved in pursuing foreign uranium supplies.⁵¹ In November 2010, during Chinese President Hu Jintao's visit to France, the French firm AREVA signed deals with CNNC and CGN to construct reactors and export uranium respectively. CGN signed a \$3.5 billion, ten-year contract with AREVA for the supply of 20,000 tonnes of uranium through 2020. Assuming 6 ktU has already been shipped during 2011–2013, there would be 14 ktU available for the plan period.

In November 2010, CGN signed a contract with the Canadian firm Cameco Corp. for the sale of 11,200 tonnes of uranium through 2025. Based on an assumed average import rate, there would be 10 ktU yet to be made available for the plan period.

Also in November 2010, CGN signed a long-term contract with Kazatomprom for 24,200 tonnes of uranium through 2020. Assuming 7 ktU had been transferred before 2014, there would be around 17 ktU available for the plan period.

On June 9, 2010, CGN-URC and Uzbekistan's Navoi Mining and Metallurgy Combine signed a 'Natural Uranium Trade Agreement' in Tashkent, Uzbekistan. China's customs authority was reported as stating that Uzbekistan was second only to Kazakhstan as a uranium supplier to the country.⁵² In 2013, 1,663 tU was supplied to China through this deal. In May 2014, CGN contracted with Uzbekistan's Navoi Mining & Metallurgy for \$800 million worth of uranium to 2021. We estimated that this is equivalent to about 8 ktU.⁵³

In addition, we assume CGN will continue to buy a total of 9 ktU from Australia during the plan period.

Thus, based on these accountable deals, CGN should have over 58 ktU available for the plan period. There are likely to be other undetailed purchases that would increase our estimate. As of 2014, CGN states that it has secured overseas uranium supplies of 79 ktU through international trade. The gap of 21 ktU could be accounted for by other purchases or the surplus from earlier deals. For now, we assume here that other purchases account for around 10 ktU (about half of the unaccounted gap).

⁵¹ Guo Lian and Chen WenLing, ed., *Research on China Bulk Mineral Sources and Coping Strategies*; Wei Qiyang, "On the Way: CGN Nuclear Fuel Supply Strategy and Security," (presentation at the Third China International Nuclear Symposium, November, 2012) http://proceedings.world-nuclear.org/CINS3/presentations/5_On_the_way_CGNPC_nuclear_fuel_security_and_strategy%20.pdf (accessed April 28, 2015).

⁵² Guo Lian and Chen WenLing, ed., *Research on China Bulk Mineral Sources and Coping Strategies*.

⁵³ Assuming uranium price for long-term contract in May, 2014 was \$100/kgU.

Consequently, CNNC and CGN would have a total about 130 ktU available for the plan period through international trade (see Table 4.1). It should be noted that several of these contracts will end around 2020. If China wants, it could have more new contracts before 2050. Meanwhile, CNNC and CGN can purchase uranium on the open spot market, from Australia and elsewhere, and nothing would stop them from continuing to do so. Thus, China would have much more overseas uranium available for the plan period through the international trade than the quantities given in Table 4.1. This abundance of supply provides sufficient time for China to find and develop additional resources.

Table 4.1: Uranium Acquired Through International Trading

Contractors	Deals	Uranium Available for 2014-2050 (ktU)
CNNC- Cameco	Signed in 2010, 10 ktU for 10 years	7
CNNC-KAZATOMPROM	Signed in 2011, 30 ktU for 2011-2020	21
CNNC-Australia	Assuming 0.25 ktU/year for the plan period	9
CNNC-others	As CNNC stated in 2009, 6-8 ktU/year secured. Unaccounted amounts assumed equivalent to: 2.7 ktU/year for 10 years.	27
CGN-AREVA	Signed in 2010, 20 ktU by 2020	14
CGN-Cameco	Signed in 2010, 11.2 ktU by 2025	10
CGN- KAZATOMPROM	Signed in 2010, 24.2 ktU by 2020	17
CGN- Uzbekistan's Navoi Mining & Metallurgy	Signed in 2014, \$800 million worth of uranium by 2021	8
CGN-Australia	Assuming 0.25 ktU/year for the plan period	9
CGN-others	CGN stated in 2014 it had secured 79 ktU through trading. Of that amount, 58 ktU can be accounted for. Here assuming others accounted for half of the unaccounted supply.	10
Total		132

Available Surplus from Past Imports

As Table 4.2 shows, China imported a total of 73 ktU from 2006 to 2013. Based on Figure 3.6, the accumulated uranium requirement from 2006 to 2013 was around 24 ktU. This means China imported about three times more uranium than domestic requirements demanded. Meanwhile, domestic production from 2006 to 2013 totaled around 10 ktU. Thus, the total surplus from imports should be around 60 ktU, which would be enough to supply a fleet of 20 GWe (2014 level) and 40 GWe PWRs (planned for 2015) for about 17 years and 9 years, respectively.

In practice, the total surplus by 2014 would be larger. For example, if China imported around 16 ktU in 2014 (as an average rate between 2010 and 2013), and uranium requirement in 2014 was estimated around 4.8 ktU, and domestic uranium production was about 1.5 ktU, the additional 13 ktU would be surplus. However, to avoid an overlap account, here we take it as the trading deal case discussed above.

Table 4.2: Annual Uranium Imports Into China 2006–2013 (tonnes)

2006-2009	2010	2011	2012	2013
8,000	17,136	16,126	12,908	18,968

Source: World Nuclear Association, “China’s Nuclear Fuel Cycle.”

Enriched Uranium Supplies

In addition, when China purchases foreign reactors, it often requires the foreign vendors to supply the first and a few subsequent loads. These deals further save China uranium resources. 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.⁵⁴
- Westinghouse will supply the first loads for its four AP1000 reactors sold to China.⁵⁵ Enriched uranium products for the first four AP1000 reactors will be supplied by Tenex of Russia from 2010 to 2021, under the 2008 agreement.⁵⁶ Moreover, reports indicated in July 2014 that China is planning to buy another eight AP1000s from Westinghouse,⁵⁷ and more can be expected.
- CGN has a contract with Urenco to supply 30% of the enriched uranium for the two Daya Bay reactors from Europe.⁵⁸
- Russia’s TVEL will supply the fuel for Tianwan 3&4 (two VVERs) until 2025.

Eventually, the total uranium saved by China through those LEU supply deals will amount to around 38 ktU (see Table 4.3).

In sum, between 2014 and 2050 foreign-origin uranium acquired through trading and LEU supply deals will have reduced Chinese natural uranium requirements by at least 230 ktU. Also it should be noted that the number will likely increase as additional deals are made.

⁵⁴ “Taishan 1&2—China,” AREVA, <http://www.AREVA.com/EN/operations-2404/china-taishan-12.html#tab=tab4> (accessed April 29, 2015).

⁵⁵ Rob Pavey, “SC Plant Readies Nuclear Fuel for China’s First AP1000 Reactor,” *The Augusta Chronicle*, March 22, 2012, <http://chronicle.augusta.com/news/business/2012-03-22/sc-plant-readies-nuclear-fuel-chinas-first-ap1000-reactor> (accessed April 29, 2015).

⁵⁶ World Nuclear Association, “China’s Nuclear Fuel Cycle.”

⁵⁷ “China Looks to Buy more AP1000 Nuclear Reactors and Is Accelerating Nuclear Reactor Approvals,” *Next Big Future*, April 21, 2014, <http://nextbigfuture.com/2014/04/china-looks-to-buy-8-more-ap1000.html> (accessed April 29, 2015).

⁵⁸ See, e.g., Guo Lian and Chen WenLing, ed., *Research on China Bulk Mineral Sources and Coping Strategies*.

Table 4.3: LEU Supply for Imported Reactors

Supplier	Deals	Saved NU for China (ktU) ^A
AREVA for two EPRs at Taishan nuclear power plant	Taishan 1 & 2 (two 1075 MWe PWRs), under construction; AREVA to supply fresh fuel for 15 years.	11.5
Westinghouse for four AP1000s	Sanmen 1 & 2, Haiyang 1 & 2 (four 1250 MWe PWRs), Westinghouse to supply four cores	2.6
Russia's Tenex for the above AP1000s	Tenex to supply 10 years of fuel for the above four AP1000s	8.7
Westinghouse for more AP1000	As of 2014, China reportedly plans to buy eight AP1000s. We assume ten AP1000s installed before 2050, and Westinghouse to supply the first loads	6.5
Urenco for Daya Bay	Daya Bay 1 & 2 (two 984 MWe PWRs), Urenco to supply 30% of fuel. We assume deal to remain from 2014 to 2050.	4.2
Russia's TVEL for VVERs	Tianwan 3 & 4 (two 1060 MWe PWRs), under construction. Planned operational in 2017. TVEL will supply LEU until 2025. Here assuming fuel supply for eight years	4.4
Total		38

^AAssuming 1 GWe PWR consumes about 173 tonnes NU per year, a replacement rate that represents about one third of the first core.

China's Overseas Exploration and Mining Activities

Beyond international trading, CNNC and CGN have been actively exploring for, and mining uranium in countries like Niger, Namibia, Zimbabwe, Kazakhstan, Uzbekistan, Mongolia, and Australia.

CNNC Projects

Since the establishment of SinoU in 2006, the firm has acquired 15 uranium-prospecting permits in Niger, Namibia, Zimbabwe, and Mongolia; the total area prospected is 8,265 square kilometers.⁵⁹ By the end of 2009, the leadership of CNNC announced that it had already secured over 200 ktU of foreign resources. However, CNNC did not disclose further details. In the following, based on available information, we have tried to estimate how much foreign uranium resources CNNC could have locked in for the China market.

Azelik/Niger: In 2006, CNNC signed an agreement to develop Niger's Azelik-Abokurum deposit and a new company, Société des Mines d'Azelik (Somina) was created in 2007 for this purpose. The Azelik Project in Niger was China's first overseas uranium project. SinoU, through a company incorporated in Hong Kong, controls 37.2% of the stocks of Azelik. Another Chinese company—ZXJOY holds a 24.8% interest; total RAR at Azelik-Abokurum plus inferred recover-

⁵⁹ Guo Lian and Chen WenLing, ed., *Research on China Bulk Mineral Sources and Coping Strategies*.

able resources amount to 15,900 tU.⁶⁰ The project has a uranium production capacity of 700 tU/year for 20 years. Total investment in the project has reached US\$2.647 billion. Work on the project officially commenced in July 2008; in March 2011 it entered a trial production phase and reached full design capacity in 2012, produced 300 tonnes of uranium by the end of 2012. Thus, we assume around 16 ktU would be available for the period 2014–2050.

Imouraren/Niger: In 2014, SinoU agreed to join AREVA's project at the Imouraren deposit in Niger. SinoU agreed to buy a 10% stake for €200 million.⁶¹ The Imouraren mine, which is being developed by AREVA, was originally to initiate production in 2014. However, AREVA has placed the mine on indefinite hold. It may not open until 2020. It was planned to have a production rate of 5,000 tU/year for 35 years. It will be the largest mining project ever undertaken in Niger, the largest open pit uranium mine in Africa, and the largest anywhere to use heap leaching. The deposit covers an area of eight kilometers by 2.5 kilometers and IAEA reports it has about 279.2 kt of uranium resources. At full production, the project's heap leaching facility will process 20,000 tonnes of ore per day with an expected 85% rate of recovery. Here, we assume a total of 280 ktU in the Imouraren deposit, and 10%—28ktU—would be available for China.

Rossing/Namibia: On August 1, 2006, CNNC was granted permission to prospect and explore the Rossing deposits in Namibia. The project is operated by Zhonghe Resources (Namibia) Development (Pty.) Ltd., a subsidiary of SinoU. SinoU owns 58% of the operator and the remaining 42% belongs to a local company.⁶² The area covered by Zhonghe Resources' license is located in the Namib Desert, which contains the Rossing uranium deposits, in the Happy Valley area some 110 kilometers northeast of Swakopmund, just east of Rossing. Between 2007 and 2012, Zhonghe Resources conducted exploration work, including geological, radioactivity, geophysical, and geochemical surveys, drilling and trenching. By 2012, Zhonghe Resources had a total drilling footage of 89,512 meters and discovered three deposits. One deposit is estimated to have indicated *in situ* resources of 25,772 tU and inferred *in situ* resources of 15,000 tU, as well as inferred resources of 11,539 tU in associated deposits elsewhere on the lease.⁶³ Zhonghe Resources is working on preliminary mine development design. As exploration work advances, it is expected that more resources will be identified. Here, we assume that current known resources of 52.3 ktU would be accessible for China during the plan period.

Langer Heinrich/Namibia: In 2014, CNNC also bought a 25% stake in Paladin Energy Ltd.'s Langer Heinrich mine in Namibia for \$190 million, entitling it to an equivalent share of output.⁶⁴ The Langer Heinrich Mine is also located in the Namib Desert, 80 kilometers east of the major seaport of Walvis Bay and about 40 kilometers southeast of the large-scale, hard-rock Rössing uranium mine—Zhonghe Resources' project. The Langer Heinrich mine has total identified

⁶⁰ Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*."

⁶¹ World Nuclear Association, "Uranium in Niger," last updated April, 2015, <http://www.world-nuclear.org/info/country-profiles/countries-g-n/niger/> (accessed April 29, 2015).

⁶² Zhang Yi, "Recent Development of Uranium Industry in China."

⁶³ Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

⁶⁴ Liu Jiayu, "The World Ninth-Largest Uranium Mine's Equity Share of Products Shipped to China This Month," (in Chinese), *Chinanews.com*, October 21, 2014, <http://finance.chinanews.com/ny/2014/10-21/6702494.shtml> (accessed May 6, 2015).

resources of 66,131 tU.⁶⁵ In 2008 it started production at a level of 1,040 tU/year and expanded to 2,030 tU/year in 2012. Further expansion aims to achieve a production level of 3,852 tU/year. The current mine model indicates a life in excess of 18 years. A first shipment of 230 tU to China was conducted in October 2014. Here, we assume one-fourth of the total identified resources—about 17 ktU—would be available to China.

Kanyeba/Zimbabwe: CNNC has been actively exploring for uranium at the deposits found in the Kanyemba district, which is about 150 miles (241 kilometers) north of Harare, Zimbabwe. The Kanyemba project is operated by Afri-Sino Mining Resources Ltd., 42% of which is owned by CNNC. Another Chinese company owns 28%, while 30% is owned by a local company.⁶⁶ CNNC was the partner which received a permit to conduct exploration work. Initial work has indicated a huge uranium potential. It is estimated that the Kanyemba deposit could hold more than 45 ktU. We assume China could access all of that amount.

Gurvanbulag/Mongolia: In March 2009, CNNC International, a 70% subsidiary of CNNC Overseas Uranium Holding Ltd. and through it, of SinoU, successfully acquired 69% of the ordinary shares of Western Prospector Group Ltd. (which was then listed in Canada). On June 14, 2009, it bought out all the shares of the company and acquired the eighteen mining licenses previously owned by Western Prospector, including those pertaining to the Gurvanbulag uranium mine in Mongolia, which is very close to the Chinese border. It is estimated that there are 8,580 tU (with an average grade of 0.18%) identified in Gurvanbulag mine, and 11,000 tU of inferred resources (with an average grade of 0.11%).⁶⁷ This project requires extensive geological work; the uranium deposit is fairly large, the uranium ore is relatively high-grade, and there is a reliable amount of resources. It is expected to yield 600 tU/year within three years once a mining permit is issued. In 2010, CNNC and the Nuclear Energy Agency of Mongolia signed a memorandum of cooperation in the area of uranium resources and nuclear energy. On June 26, 2012, CNNC Mongolia Project Co. and the Nuclear Energy Agency of Mongolia signed an Agreement for Gurvanbulag Uranium Mine Early-Stage Mining Work. In 2014, a CNNC assessment report on the economic and technical feasibility of the project was approved, providing the basis for a mining rights permit.⁶⁸

Mongolia is well-endowed with uranium resources. Based on the 2014 Red Book, as of January 1, 2013, recoverable uranium resources in Mongolia attributable to the identified resources category amounted to 141,521 tU. It is reported that as of 2014 China had already secured uranium resources in the country of up to 10 ktU.⁶⁹ China hopes to lock up more uranium resources in Mongolia.

Zhalpak/Kazakhstan: In 2007, CNNC and Kazatomprom, a state-run energy company that oversees uranium production in Kazakhstan, signed a framework strategic cooperation agreement. Late in 2007, Kazatomprom signed an agreement with CNNC and CGN for the two

⁶⁵ Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

⁶⁶ Zhang Yi, “Recent Development of Uranium Industry in China.”

⁶⁷ See, e.g., Guo Lian and Chen WenLing, ed., *Research on China Bulk Mineral Sources and Coping Strategies (in Chinese)*.

⁶⁸ CNNC, “CNNC has made significant progress in the first uranium projects in Mongolia,” (in Chinese), July 11, 2014, <http://www.sasac.gov.cn/n1180/n1226/n2410/n314244/15957158.html> (accessed May 6, 2015).

⁶⁹ Guo Lian and Chen WenLing, ed., *Research on China Bulk Mineral Sources and Coping Strategies (in Chinese)*.

Chinese firms to take a 49% stake in two uranium mine joint ventures and to supply 2000 tU/year from them. In 2008, CNNC and Kazatomprom further signed a “long-term nuclear cooperation projects” agreement under which CNNC is to invest in a uranium mine.⁷⁰ It is reported that CNNC’s Zhalspak project will produce 640 tU/year.⁷¹ However, it is not clear when CNNC began or will begin the exploration and mining work. As an estimate, here we assume CNNC could obtain 20 ktU from the project. As a comparison, the CGN and Kazatomprom cooperation projects at Irkol and Semizbai (discussed in the following text) have a joint resource of 45 ktU, and can attain a production level of 1,200 tU/year for 30 years. CNNC may wish to have access to no less uranium from Kazakhstan than its competitor—CGN.

Consequently, as shown in Table 4.4, we estimate that CNNC could have a possible total overseas uranium of 198 ktU. This is consistent with a CNNC statement about its secured overseas uranium which put the total at 200 ktU.⁷² Some of those mines could be not operational in the near future, but could be available before 2050 as the period we discuss. Moreover, during the plan period (2014–2050), new projects could develop or replace some current projects. Of course, all of those estimates could be adjusted to take into account new developments and as new accurate information becomes available.

Table 4.4: CNNC’s Overseas Mining Activities

Mines/ Country	Chinese Equity (%)	Possible Uranium for China (ktU)
Azelik/Niger	37.2% SinoU; 24.8% ZXJOY (China), 38% local. RAR:15.9ktU	16
Imouraren/Niger	10% (negotiating with AREVA by 2014). RAR: 276.2ktU. Assuming 10% for China, around 27.6 ktU	28
Rosing/Namibia	58% SinoU; 42% local, one deposit- RAR: 52.3 ktU; more expected.	52
Langer Heinrich/Namibia	25% RAR: 66.131ktU. Assuming 25% for China, around 17 ktU.	17
Kanyeba/Zimbabwe	42% SinoU, 28% other Chinese company, 30% local. Estimated uranium resources: 45.5 ktU.	45
Gurvanbulag/Mongolia	69% CNNC, 31% local. RAR: 19.6ktU	20
Zhalspak/Kazakhstan	CNNC and Kazatomprom signed on to the project in 2008. We assume around 20 ktU available for the plan period.	20
Total		198

⁷⁰ World Nuclear Association, “Uranium and Nuclear Power in Kazakhstan,” last modified April, 2015, <http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Kazakhstan/> (accessed May 3, 2015).

⁷¹ “Chinese Equity in Kazakh Uranium Mines Confirmed,” *World Nuclear News*, November 18, 2008, http://www.world-nuclear-news.org/IT-Chinese_equity_in_Kazakh_uranium_mines_confirmed-1811085.html (accessed April 29, 2015).

⁷² Duan Xinxin, “Nuclear Power: ‘Power China’ target is coming.”

CGN Projects

Since 2006, a CGN subsidiary, CGN Uranium Resources Co. Ltd. (CGN-URC), has been actively exploring for and mining uranium in countries such as Kazakhstan, Namibia, Australia, and Uzbekistan. Consequently, in 2013, the head of CGN stated that the firm had secured approximately 308,000 tonnes of overseas natural uranium resources by the end of 2012.⁷³

CGN-URC experts have revealed that CGN's criteria for the selection of projects include: regional diversification (i.e., distribution across Africa, Central Asia, Australia, etc.); a stable and positive political and business environment (i.e., a stable government, no terrorist threat, a government supportive of uranium mining); rational return on investment (i.e., low costs); and controllable risk exposure. The firm is also cautious about involvement in grassroots projects with high risk.⁷⁴

Irkol and Semizbai/Kazakhstan: In December 2006, CGN and Kazatomprom signed a Strategic Agreement for a Mutually Beneficial Partnership. In September 2007, two agreements were signed in Beijing between Kazatomprom and CGN on Chinese participation in Kazakh uranium mining joint ventures and on reciprocal Kazatomprom investment in China's nuclear power industry. In October 2008, a further agreement was signed on cooperation in uranium mining, fabrication of nuclear fuel for power reactors, long-term trade of natural uranium, generation of nuclear electricity, and construction of nuclear power facilities. A CGN subsidiary, Sino-Kazakhstan Uranium Resources Investment Co., has invested in two Kazakh uranium mines, Irkol and Semizbai, through the Semizbai-U LLP joint venture. GCNPC holds a 49% stake in the venture, while Kazatomprom holds the other 51%.⁷⁵ Semizbai-U is CGN's first mine successfully performing operations and owned through a joint venture with a reputable world-class supplier.

The CGN-URC experts estimate the total uranium resources at the two sites to be around 45 ktU.⁷⁶ Initial production started in 2008. The two sites now have a joint production capacity of 1,200 tU/year. The Semizbai and Irkol mines have produced 4.2 ktU as of the end of 2012.⁷⁷ Almost all of that has been transferred to China. Here, we assume a total of 45 ktU would be available to China.

Husab/Namibia: In 2012 CGN acquired the Husab Project in Namibia. The project remains under construction and operations are expected to begin in 2015.⁷⁸ Swakop Uranium (Pty.) Ltd. (SUL) is the owner of the Husab Uranium Project, which is located near Swakopmund on the west coast of Namibia. Taurus Minerals Ltd. of Hong Kong (60% CGN-owned, 40% held by the China-Africa Development Fund) holds a 90% stake in the project. Epangelo, the Namibian state-owned mining company, has a share of 10%.

⁷³ He Yu, "Uranium Resource for China's NNP Can Meet the Needs of its Nuclear Power Development."

⁷⁴ Wei Qiyao, "CGN's Global Uranium Investment."

⁷⁵ Wei Qiyao, "CGN's Global Uranium Investment."

⁷⁶ Wei Qiyao, "CGN's Global Uranium Investment."

⁷⁷ Red Book 2014:OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

⁷⁸ Guo Lian and Chen WenLing, ed., *Research on China Bulk Mineral Sources and Coping Strategies*; Wei Qiyao, "CGN's Global Uranium Investment."

In December 2011, the Namibian government granted a mining license to SUL. At the end of 2012, the total resource base at the Husab deposit amounts to identified *in situ* resources of 196,490 tU.⁷⁹ Recently reports indicate more resources have been discovered at the deposit, increasing the total to 243 ktU.⁸⁰ More is expected to be found in the surroundings. The construction of the mine commenced in April 2013, and production is expected to begin in 2015 with a 24-month ramp-up to full production capacity at 5,770 tU/year in 2017. Husab is currently the third-largest uranium deposit in the world. Husab is a milestone in implementation of CGN's fuel security strategy. Product will be supplied not only to CGN but also to global utilities. The development of Husab will benefit the fuel security of end-users worldwide. The head of CGN stated that the Husab uranium resource would be large enough to fuel 30 1 GWe PWRs for 30 years of operations (if we assume a 1 GWe PWR needs 200 tU/year, the statement means there are roughly 180 kt of recoverable uranium, which is comparable to the identified resources). Assuming 90% of the total resources is for China, then around 220 ktU would be available over the course of the plan period.

Energy Metals/Australia: On September 8, 2009, through an investment vehicle, China Uranium Development Co. Ltd., CGN-URC initiated the acquisition of an Australian uranium exploration company, Energy Metals Ltd., spending US\$72.10 million to acquire 70% of the shares of the firm. Energy Metals has nine uranium projects. At the moment, a key project is the Bigirlyi sandstone uranium deposit prospecting project in Australia's Northern Territory. The head of Energy Metals states that the firm controls a total of about 18.8 kt of U_3O_8 (around 16 ktU) through five projects including the Bigirlyi project.⁸¹ Here, we assume 16 ktU would be available to China.

Boztau/Uzbekistan: In September 2009, CGN-URC embarked upon a joint venture, named Sino-Uz Uranium Resources Co. Ltd. (or Uz-China Uran LLC), with Uzbekistan's State Committee for Geology and Mineral Resources (Goskomgeo). CGN-URC holds 50% of the shares. The venture has focused on prospecting and mining black shale uranium deposits, in particular the Boztau uranium exploration project in the Central Kyzylkum desert of the Navoi region of Uzbekistan. Some 5,500 tU of resources have been reported.⁸² Over the period 2011–2013, CGN-URC was to develop technology for the separate production of uranium and vanadium from these black shale deposits with a view to commencing production from 2014.

According to the 2011 Red Book, Uzbekistan has 96 ktU in RAR plus inferred resources, at \$130/kg of uranium. In February 2014, Goskomgeo reported resources of 138.8 ktU in sandstones and 47 ktU in black shale.⁸³ Uz-China Uran, the Uzbek-Chinese joint venture, plans to complete tests of technology to separately mine uranium and vanadium in the first half of 2013,

⁷⁹ Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

⁸⁰ "CGN and Namibia organizations signed the relevant agreement on the Husab uranium project", *CGN news*, April 9, 2014, <http://www.cgnpc.com.cn/n471046/n471126/n471156/c597862/content.html> (accessed May 6, 2015).

⁸¹ Weidong Xiang, "CGNPC's Uranium Investment & Experience in Australia," <http://www.nt.gov.au/d/acmis/pdf/presentations/InvestingInAustralia2/WeidongXiangEnglish.pdf> (accessed April 29, 2015).

⁸² World Nuclear Association, "Uzbekistan Uranium," last modified April, 2015, <http://www.world-nuclear.org/info/country-profiles/countries-t-z/uzbekistan/> (accessed April 29, 2015).

⁸³ World Nuclear Association, "Uzbekistan Uranium."

and to start mining uranium in the Navoi region of Uzbekistan in 2014.⁸⁴ In 2010–2011, the venture carried out exploration work in the contracted area and invested over US\$2 million. After exploration, several uranium fields had been found. According to Goskomgeo, forecast uranium resources in the Boztau area total about 5,500 tU. In line with the terms of the venture’s creation, the Chinese company will receive a primary right to purchase products of Uz-China Uran at world prices. We assume China could obtain around 6 ktU from the project.

Others: It has been reported that CNNC and CGN have also been interested in other countries’ uranium resources. In November 2007, CGN signed an agreement with AREVA to take a 24.5% equity stake in its UraMin subsidiary (now AREVA Resources Southern Africa). In October 2008, AREVA announced that a further 24.5% would be taken up by other “Chinese sovereign funds.” UraMin was proposing mines in Namibia, South Africa, and the Central African Republic. China agreed to buy more than half of the uranium from UraMin over the lifetime of its three deposits—a total amount of over 40 ktU through 2022.⁸⁵ If the deal comes to fruition, CGN would obtain around 20 ktU from these deposits. However, the future of the deal is not clear.

Consequently, as summarized in Table 4.5, we estimate that CGN has possible foreign uranium resources of about 310 ktU, which is close to the 308 ktU announced in a CGN statement.⁸⁶ If we assume all these resources are *in situ*, and assume a recovery rate of 80%, recoverable uranium resources would total 250 ktU.

Thus, CNNC and CGN would have a total of about 400 kt recovered uranium resources available for the plan period through overseas exploration and mining. However, it should be noted that all estimates could be adjusted to acknowledge new developments and new accurate information as it becomes available. It is more likely to be higher than the given figure due to reserve growth effects – once recovery starts at a mine, more resources are usually found there. Moreover, between now and 2050, it may well be possible for China to enter into additional agreements that would secure still more resources.

Sinosteel Projects

Besides CNNC and CGN, China’s Sinosteel Corporation (Sinosteel) has also been involved in uranium projects abroad. On February 7, 2007, Sinosteel and Australia’s PepinNini Minerals Ltd. signed a joint venture agreement for joint participation and cooperation in the development of uranium deposits in South Australia. Sinosteel established a company in Australia – Sinosteel-Southern Australia Uranium Mining Co.—and acquired 60% of the shares of a subsidiary of PepinNini Minerals Ltd. The joint venture will begin mining work at two uranium deposits in southern Australia. Sinosteel will sell all the uranium produced back to China, while CNNC will be responsible for the processing of this uranium.

⁸⁴ “Uz-China Uran Can Start Uranium Mining in 2014,” *Uzbekistan Daily*, November 28, 2012, <http://www.uzdaily.com/articles-id-21102.htm> (accessed April 29, 2014).

⁸⁵ “China’s Nuclear Fuel Cycle,” World Nuclear Association.

⁸⁶ He Yu (the president of the board of CGPNC), “Uranium Resource for China’s NNP Can Meet the Needs of its Nuclear Power Development.”

Table 4.5: CGN's Overseas Mining Activities

Mines/Country	Chinese Equity (%)	Possible Uranium for China (ktU)
Irkol and Semizbai/Kazakhstan	49% SinoU; 51% Kazatomprom, RAR: about 45ktU	45
Husab/Namibia	90 % Chinese company; 10% local, RAR:248 ktU; more expected. If 90% for China, 223ktU.	220
Energy Metals/ Australia	70% CGN. Projects total 16 ktU.	16
Boztau/Uzbekistan	50% CGN, 50% local. Estimated uranium resources: 5.5 ktU.	6
South Africa, etc	In 2008, CGN agreed 49% of ARE-VA's UraMin, which owned 40 ktU; over half is for China. If the deal comes to fruition, it could provide around 20 ktU to China.	20
Total		307

As summarized in Table 4.6, China will have about 230 ktU from international trade and LEU products deals, and about 400 kt of recoverable uranium resources in overseas exploration and mining projects. Combined with domestic known uranium resources of 200 ktU, supplies could total 830 ktU, more than enough to meet demand of 660 ktU for a nuclear installation scenario with 343 GWe (the high growth case) by 2045. However, this total would not be enough to secure supplies through 2050 under the high-growth scenario, as further expansion to 400 GWe of installed capacity would require total uranium resources of 950 ktU. However, as discussed before, the gap of 120 ktU would be easily filled by continuing increases in known domestic resources and overseas mining and trading.

Table 4.6: A Summary of China's Pursuit of Uranium Overseas

Items	Possible Recovered Uranium Resources for China (ktU)
Traded uranium	132
LEU deals	38
Surplus (existing inventory)	60
CNNC mining	160 (198 ktU of <i>in situ</i> resources, recovery rate of 80%)
CGN	250 (307 ktU <i>in situ</i> resources, recovery rate of 80%)
Others (SinoSteel, etc.)	N/A
Total	632 (three times known domestic resources)

V: Security of Uranium Supply and World Uranium Resources

One major motivation listed by experts in advocating for civilian plutonium reprocessing and recycling in China is “saving uranium.” They argue that China’s own uranium resources will be insufficient to supply the quantities needed for an ambitious future nuclear power program. They express concern and claim that China should not be heavily reliant on international uranium supplies, which could be at risk of disruption due to global political or economic changes. However, this argument only makes sense if China’s energy system becomes much more dependent on nuclear energy, and worldwide uranium resources become depleted or prohibitively expensive, or uranium suppliers are to collude to raise prices or limit supplies. These conditions are unlikely to be met in the foreseeable future, however. The uranium market is too diversified for this to be a very plausible scenario.

Thus, when considering the energy security issues related to nuclear power, the key issue is the uninterrupted availability of world uranium sources at a price affordable to China. In the following section, we will examine how much world uranium is available, whether China can access those world resources, and whether those resources will be available at an affordable cost over the very-long-term. Finally, if China becomes seriously concerned about the depletion of world uranium supplies, it can easily and inexpensively establish a “strategic” uranium stockpile.

World Uranium Resources

The newly issued Red Book 2014 estimates that total identified global uranium resources (reasonably assured and inferred) amounted as of January 1, 2013, to 7,635,200 tU in the highest cost category (<USD 260/kgU or <USD 100/lb U₃O₈) which was reintroduced in 2009 (see Table 5.1), an increase of 7.6% compared to the total reported in 2011.⁸⁷ This increase adds almost ten years of global reactor supply to the existing resource base. Based on uranium requirements in 2012 (about 61,600 tU/year), if there was no growth of nuclear power, total identified resources would be sufficient for about 124 years of supply to the global nuclear power fleet.

Moreover, the Red Book 2014 estimates total undiscovered resources (prognosticated resources and speculative resources—PR and SR respectively) to amount as of January 1, 2013, to 7.7 MtU, including around 4.7 MtU in the highest cost category (<USD 260/kgU) and around 3 MtU in an unassigned cost category (see Table 5.2).⁸⁸ However, reporting of undiscovered resources is incomplete; some countries did not report their data. For instance, the United States reported to the Red Book 2011 a total of 2.6 MtU in SR and PR, but did not report to the 2014 edition because previous estimates completed in 1980 need reevaluation to determine their accuracy. In addition, China’s reporting of undiscovered resources to this new edition is just 7,700 tU. However, China is believed to have a uranium potential of 2 MtU. Combining U.S. and Chinese potentials, total undiscovered resources could amount to over 12.3 MtU. However, it is worth noting that only 37 countries report uranium resources of any form, so even the 12.3 MtU figure is conservative.

⁸⁷ Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

⁸⁸ Undiscovered resources (*prognosticated* and *speculative*) refer to resources that are expected to occur based on geological knowledge of previously discovered deposits and regional geological mapping. *Prognosticated resources* (PR) refer to those expected to occur in known uranium provinces, generally supported by some direct evidence. *Speculative resources* (RS) refer to those expected to occur in geological provinces that may host uranium deposits. Both prognosticated and speculative resources require significant amounts of exploration before their existence can be confirmed and grades and tonnages can be more accurately determined. All PR and SR are reported as *in situ* resources (see Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*).

Table 5.1: Identified Global Recoverable Uranium Resources

	<USD 40/kgU	<USD 80/kgU	<USD 130/kgU	<USD 260/kgU
Reasonably Assured	507.4	1,211.6	3,689.9	4,587.4
Inferred Resources	175.5	745.1	2,204.0	3,048
Total Identified Resources	682.9	1,956.7	5,902.9	7,635.2

Note: Data as of January 1, 2013, in 1,000 tU.

Thus, the total conventional uranium potential (total identified uranium plus total undiscovered resources) would be around 20 MtU, which would be sufficient for over 300 years of supply for the global nuclear power fleet at 2012 uranium requirement levels (see Table 5.3). However, significant exploration and development is required to convert these resources into identified resources. Of course, as more power reactors are installed in the future, more uranium will be required compared to 2012. This will drive exploration work and technical advances, making more deposits economically feasible.

It should be noted that in past experience total known resources have increased faster than resources were depleted, because of increasing exploration work and advances in technology. As shown in Figure 3.2, known Chinese uranium resources had been increased by 2012 over three-fold since 2004 as the government significantly increased its exploration expenditure, driven mainly by the perception that uranium demand will increase as its plans for nuclear power development unfold. Similarly, as shown in Figure 5.1, global identified uranium resources have more than doubled since 1975, in line with increasing expenditure on uranium exploration, even as over 2 MtU has been used.⁸⁹ The World Nuclear Association states that “[i]ncreased exploration expenditure in the future is likely to result in a corresponding increase in known resources, even as inflation increases costs of recovery and hence tends to decrease the figures in each cost category.”⁹⁰

Further, there also exist considerable unconventional resources, including phosphate deposits, black shale, and coal ash. It is estimated that worldwide totals of phosphate-related resources could contain as much as 22 MtU. Almost 9 MtU is estimated in four countries alone—Jordan, Mexico,

Table 5.2: Total Undiscovered Resources (PR and SR)

Resource Category	<USD 130/kgU	<USD 260/kgU	Cost Unassigned
Prognosticated	1,222.8	1,755.5	N/A
Speculative	2,639.3	2,946.5	2,995.7
Total	3,862.1	4,702	2,995.7

Note: Data as of January 1, 2013, *in situ* resources, in 1,000 tU.

⁸⁹ World Nuclear Association, “Supply of Uranium,” last modified October 8, 2014, <http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Supply-of-Uranium/> (accessed April 29, 2015).

⁹⁰ “Supply of Uranium,” World Nuclear Association.

Table 5.3: Lifetime of Uranium Resources

Identified Recoverable Resources (7.6MtU)	Total Conventional Resources (20MtU)	Total Conventional Resources (20 MtU) plus Phosphates (22MtU) (i.e., a total of 42 MtU) ^A
124	325	682

Note: Years of supply at 2012 reactor requirements of 61,600 tU/year).

^AAccording to previous reviews, worldwide totals of phosphate-related resources could total as much as 22 million tU. See.e.g., OECD-NEA, *Trends Towards Sustainability in the Nuclear Fuel Cycle*, Paris, France: OECD-NEA, 2011, <http://www.oecd-neo.org/ndd/pubs/2011/6980-trends-fuel-cycle.pdf> (accessed April 29, 2015).

Morocco, and the United States, according to previous reviews.⁹¹ Of 5.2 MtU in worldwide black shale, approximately 4.2 MtU is found in the Chattanooga deposit in the United States and the Ronneburg deposit in Germany. Around 0.7 MtU may also be recoverable from lignite.⁹² But it may only be economic as a byproduct.

Finally, it should be noted that many studies have shown that the Red Book estimates are probably conservative.⁹³ These studies point out that much more uranium resources in the earth's crust can be made available when the uranium ore grade standards are decreased or the price of uranium is increased. For instance, Deffeyes and MacGregor developed a classic model to estimate uranium content and concentration in the earth's crust which indicated the distribution of ore grade versus amount was well approximated by a log-normal distribution (Figure 5.2). They suggested that a reduction in ore grade by a factor of ten increases the amount of available uranium by a factor of 300.⁹⁴ As a first-order estimate of the relationship between amount and concentration based on Deffeyes and MacGregor's model, it is estimated that the slope of Deffeyes and MacGregor's curve falls between 2.5 and 3.5 at the ore grades currently being mined—possessing 0.1 to 1.0% U₃O₈ content.⁹⁵ This means that, if we can explore uranium ore an order of magnitude lower in grade, the resource base would expand by a factor ranging from 10^{2.5} (i.e., an increase of 300-fold) to 10^{3.5} (i.e., an increase of 3000-fold). The total amount of uranium in the earth's crust is estimated to be 80 trillion tonnes.⁹⁶

⁹¹ OECD-NEA, *Trends Towards Sustainability in the Nuclear Fuel Cycle*, Paris, France: OECD-NEA, 2011, <http://www.oecd-neo.org/ndd/pubs/2011/6980-trends-fuel-cycle.pdf> (accessed April 29, 2015).

⁹² Red Book 2014: OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

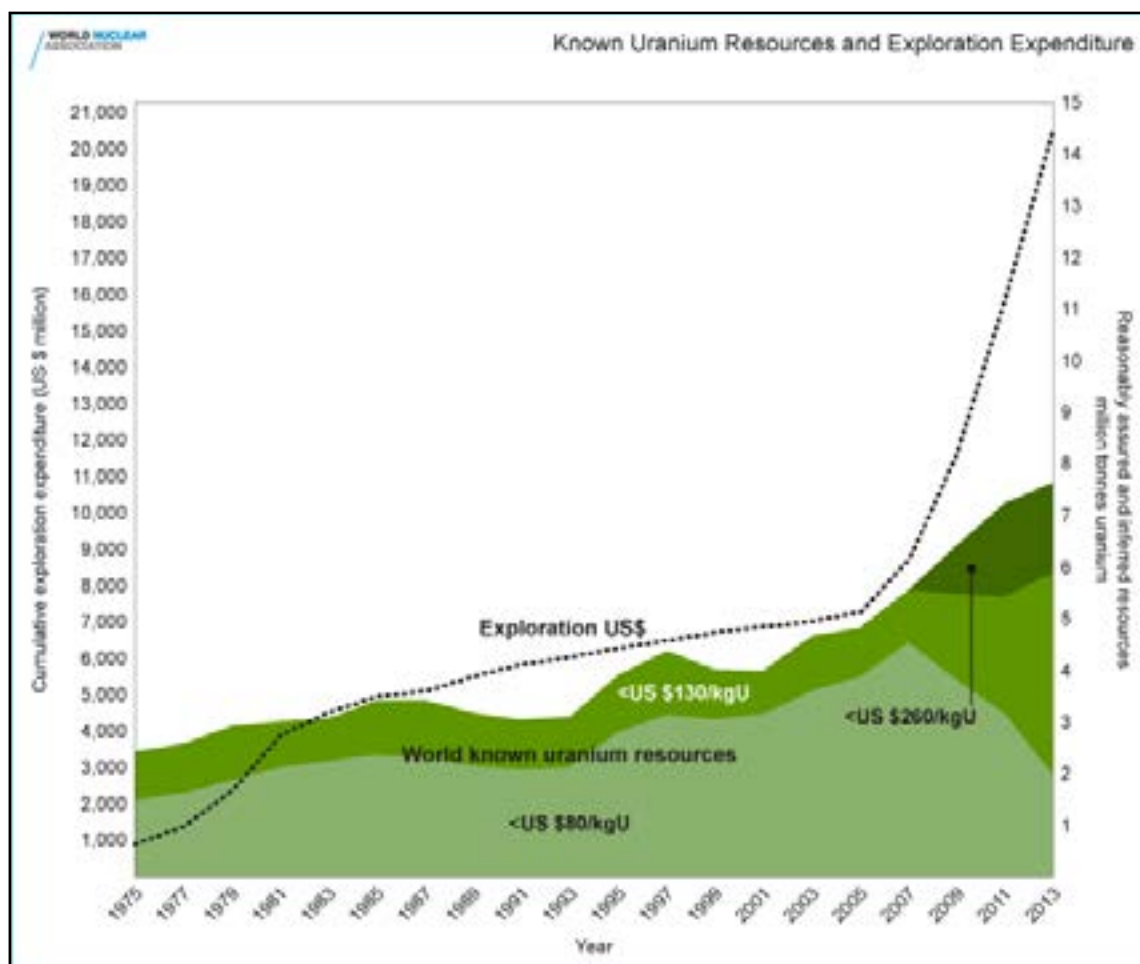
⁹³ See, e.g., Erich Schneider and William Sailor, "Long-term Uranium Supply Estimates," *Nuclear Technology*, Vol. 162, No. 3 (June 2008), p. 379–87; Matthew Bunn, Steve Fetter, John Holdren, and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Cambridge, Massachusetts: Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School of Government, December 2003). <http://belfercenter.ksg.harvard.edu/publication/2089/> (accessed April 29, 2015); Massachusetts Institute of Technology, "The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study," (Cambridge, Massachusetts: MIT, 2011). http://web.mit.edu/mitei/research/studies/documents/nuclear-fuel-cycle/The_Nuclear_Fuel_Cycle-all.pdf (accessed April 29, 2015).

⁹⁴ K.S. Deffeyes and I.D. MacGregor, "World Uranium Resources," *Scientific American*, Vol. 242, No. 1 (1980), p. 66.

⁹⁵ Erich Schneider and William Sailor, "Long-term Uranium Supply Estimates." It is reported the average grade of deposits being mined has held nearly level at 0.1% U₃O₈ (1000 ppm U) since the beginning of large-scale uranium production (see G. Mudd, "Sustainable Mining: An Evaluation of Changing Ore Grades and Waste Volumes," (International Conference on Sustainable Engineering & Science, Auckland, NZ, 2004). Also Erich Schneider, "Uranium: Scarce or Sustainable?" (presented at the Harvard-Peking Workshop on Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011).

⁹⁶ Eric Schneider and William Sailor, "Long-term Uranium Supply Estimates."

Figure 5.1: World Known Uranium Resources and Exploration Expenditure



Source: World Nuclear Association, “Supply of Uranium.”

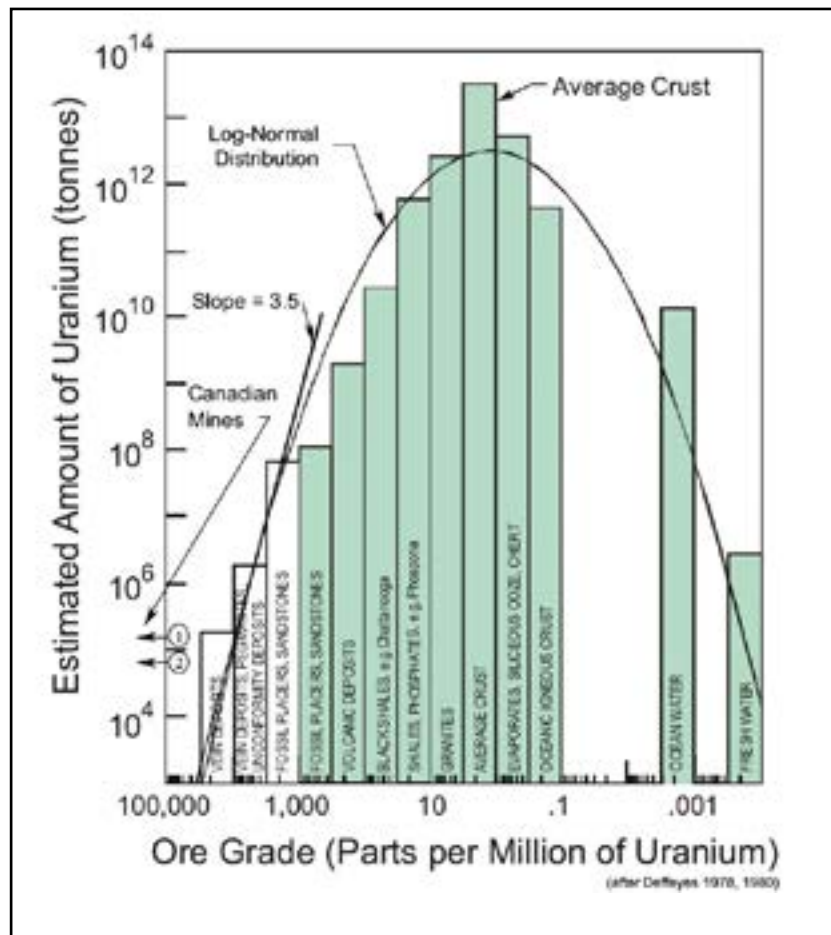
In addition, experts who have investigated the subject suggest an exponential relationship between available resources and price.⁹⁷ Assuming the cost of extracting a unit mass of uranium varies linearly with the inverse of the ore grade and that the uranium price P (in \$/kgU) is equal to the long-term marginal production cost, then the resources as a function of price would be:

$$Q/Q_0 = (P/P_0)^\varepsilon \quad (\text{A.1})$$

Where Q is the total uranium resource (MtU) recoverable at price P (\$/kgU), Q_0 is the quantity recoverable at some reference price P_0 and ε is the long-term price elasticity of supply. Given that recent uranium prices have ranged around \$80/kgU, here we select the reference point (P_0, Q_0) as the value given in the 2014 Red Book for uranium recoverable at \$80/kg, i.e., $P_0 = \$80/\text{kgU}$, $Q_0 = 2\text{MtU}$.

⁹⁷ Erich Schneider and William Sailor, “Long term Uranium Supply Estimates”; Matthew Bunn, Steve Fetter, John Holdren, and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*.

Figure 5.2: Distribution of Uranium in the Earth's Crust



Note: On this log-log plot, the slope of the leading edge is the “supply elasticity exponent.”

Source: K.S. Deffeyes and I.D. MacGregor, “World Uranium Resources,” and Erich Schneider and William Sailor, “Long term Uranium Supply Estimates.”

Different models have suggested varied price elasticities of supply.⁹⁸ For instance, according to Deffeyes and MacGregor’s crustal model, i.e., a ten-fold decrease in ore grade would lead to a 300-fold increase in resources, in the above equation, $\epsilon = 2.48$ (i.e., $\log(300)/\log(10)$). Using the Red Book estimate of 2 MtU recoverable at \$80/kgU or less gives 7 MtU and 37 MtU available at \$130/kgU or less and \$260/kgU or less, respectively (see Table 5.3).

On the basis of analogies with other metal minerals, The World Nuclear Association (WNA), formerly the Uranium Institute, concludes that “a doubling of price from present levels could be expected to create about a tenfold increase in measured economic resources, over time, due both to increased exploration and the reclassification of resources regarding what is economically recoverable.”⁹⁹ The WNA suggests that $\epsilon = 3.32$ [i.e., $\log(10)/\log(2)$]. As a result, based on equation A.1 and the reference point (\$80/kgU, 2MtU), we can estimate that 10 MtU and 100 MtU would be available at \$130/kgU or less and \$260/kgU or less, respectively.

⁹⁸ Schneider and Sailor, “Long term Uranium Supply Estimates.”

⁹⁹ World Nuclear Association, “Supply of Uranium.”

Also, based on the amounts of uranium recently estimated to be available in the United States at \$30/kgU and \$50/kgU, the Generation-IV Fuel Cycle Crosscut Group advising the U.S. Department of Energy's Office of Nuclear Energy suggested an exponential relationship between resources and price, and estimated that the exponent ϵ in equation A.1 might be as low as 2.35.¹⁰⁰ If so, we can estimate 6 MtU and 32 MtU available worldwide at \$130/kgU or less and \$260/kgU or less, respectively.

Table 5.4 summarizes these estimates. As shown in the table, these models suggest that uranium availability will be significantly greater than the Red Book numbers imply. Also, based on surveys of supply curves in the literature, some studies conclude that “the Red Book data should be viewed as a conservative lower bound on supply in the short term and a reasonable point of departure for extrapolation of longer-term supply estimates.”¹⁰¹

It should be noted that the exponential model implies that the cost of uranium will increase as production moves to poorer and poorer grades of ore. But the model fails to take into account changing technology. As will be discussed later, the real story for virtually all mined minerals has been declining, not growing, real prices, over the course of the 20th century and into the 21st.

Table 5.4: Uranium Resource Estimates

Source	Long-term Elasticity of Supply, ϵ	Recoverable Resources (MtU)	
		$\leq \$130/\text{kgU}$	$\leq \$260/\text{kgU}$
Uranium Information Centre (doubling price=ten-fold increase in known resource)	3.32	10	100
Deffeyes & MacGregor (ten-fold decrease in ore grade=300-fold increase in resource)	2.48	7	37
Gen-IV Group (based on U.S. resources for various mining methods)	2.35	6	32
Red Book 2014 (recoverable identified resources)		5.9	7.6
Red Book 2014 (identified plus undiscovered) plus U.S. and China potential		10	20

Note: Table based on Equation A.1.

¹⁰⁰ U.S. Department of Energy, *Generation IV Roadmap: Report of the Fuel Cycle Crosscut Group* (Washington, DC: DOE, March 18, 2001), <http://energy.gov/sites/prod/files/GenIVRoadmapFCCG.pdf> (accessed April 29, 2015), p. 1–30.

¹⁰¹ Erich Schneider and William Sailor, “Long-term Uranium Supply Estimates.”

Moreover, the world's oceans contain around 4.5 billion tU, sufficient for over 70,000 years of supply for the global nuclear power fleet at 2012 uranium requirement levels, and seawater is viewed as an almost inexhaustible natural resource. Research on extraction of uranium from seawater was carried out in Germany, Italy, Japan, the United Kingdom and the United States from the 1950s through the 1980s and more recently in Japan and the United States. To date, research has demonstrated that uranium can be recovered from seawater by using modern adsorbents. While the extraction technology has been proven on a laboratory scale, industrial application has not yet been achieved.

A recent study provides an independent cost estimate for uranium production from seawater through the braid-type adsorbent recovery system proposed by the Japan Atomic Energy Agency (JAEA).¹⁰² In cross-checking the JAEA assessment, the author estimates that with a fresh adsorbent capacity of 2 kgU/t ads and six recycles, the unit yields a production cost of \$1,230/kgU. If capacity and the number of recycles increases to 6 kg U/t ads and 20, respectively, the uranium production cost drops to \$299/kgU.

In 2012, researchers at the U.S. Department of Energy (DOE) more than doubled the amount of uranium that can be extracted from seawater using Japanese technology developed in the late 1990s, and reduced overall production costs from about \$1,230/kgU to \$660/kgU.¹⁰³ The technology Japanese researchers pioneered uses long mats of braided plastic fibers, embedded with uranium-adsorbent amidoxime, to capture trace amounts of uranium in the ocean.¹⁰⁴

To make this process more economical, DOE researchers used plastic fibres with ten times more surface area than the Japanese design, allowing for a greater degree of absorption on a similar platform. They tested their new design at the Pacific Northwest Nuclear Laboratory's marine testing facility in Washington State. The U.S. DOE reportedly funded work using polymer absorbent strips that resulted in production costs of \$610/kgU in 2014.¹⁰⁵

It is expected that further cost reductions can be achieved as progress in developing improved adsorbent materials is made. However, this would require additional investment in R&D.

Finally, can our estimates of uranium resources meet expanded nuclear power demand in the future? In the new IAEA report *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050*¹⁰⁶, the IAEA foresees continued growth in nuclear capacity into the future. The report projects that:

¹⁰² Erich Schneider and Darshan Sachde, "The Cost of Recovering Uranium from Seawater by a Braided Polymer Adsorbent System," *Science & Global Security*, Vol. 21, Issue 2 (2013), p.134–163.

¹⁰³ Will Ferguson, "Record Haul of Uranium Harvested from Seawater," *New Scientist*, August 29, 2012, <http://www.newscientist.com/article/dn22201-record-haul-of-uranium-harvested-from-seawater.html#.VLK8k3shGDk> (accessed April 29, 2015).

¹⁰⁴ Sugo, Takanobu, et al., "Recovery System for Uranium from Seawater with Fibrous Adsorbent and Its Preliminary Cost Estimation," *Journal of the Atomic Energy Society of Japan*, Vol. 43, No. 10 (2001), p. 1010–1016; Masao Tamada, Noriaki Seko, Noburu Kasai, and Takao Shimizu, "Cost Estimation of Uranium Recovery from Seawater with System of Braid Type Adsorbent," *Transactions of the Atomic Energy Society of Japan*, 2006, p. 358–363.

¹⁰⁵ World Nuclear Association, "Supply of Uranium."

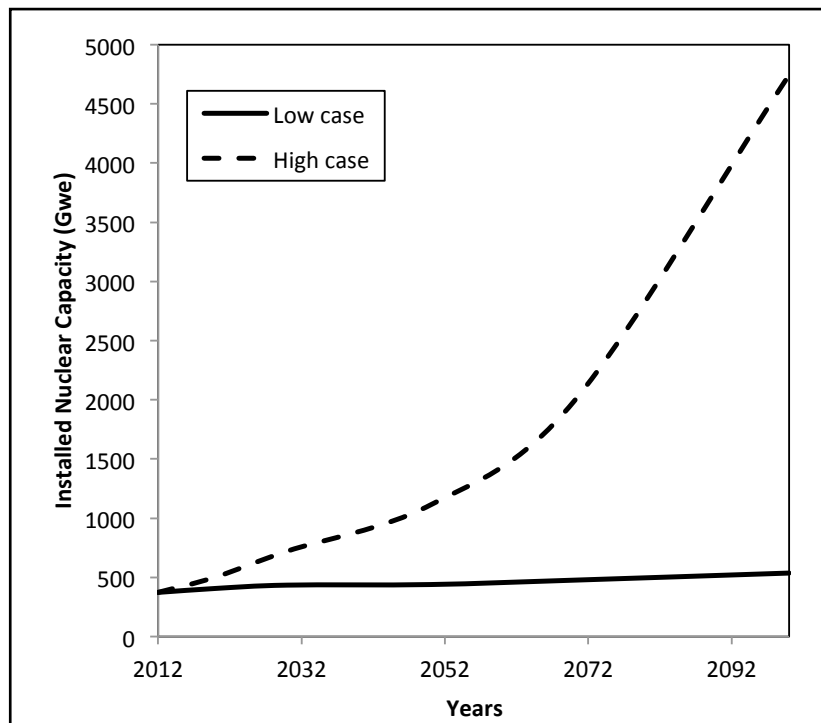
¹⁰⁶ *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050*, International Atomic Energy Agency: Vienna, Austria, 2013, http://www-pub.iaea.org/MTCD/publications/PDF/RDS-1-33_web.pdf (accessed April 29, 2015).

A. Under a low-growth scenario, global installed nuclear capacity would grow from 373 GWe in 2012 to 407 GWe in 2020, 435 GWe in 2030, and 440 GWe in 2050.

B. Under a high-growth scenario, global installed nuclear capacity would grow from 373 GWe in 2012 to 503 GWe in 2020, 722 GWe in 2030, and 1,113 GWe in 2050. To project a global installed nuclear capacity through 2100, we assume average exponential growth rates of 2.9% and 0.4% for the high-growth and low-growth cases, respectively.¹⁰⁷

We project that global installed nuclear capacity will grow by 2100 to 537 GWe and 4,745 GWe for the low-growth and high-growth cases, respectively (see Figure 5.3). In practice, the high-growth case would be as a bounding case.

Figure 5.3: A Projection of Nuclear Power (2012–2100)



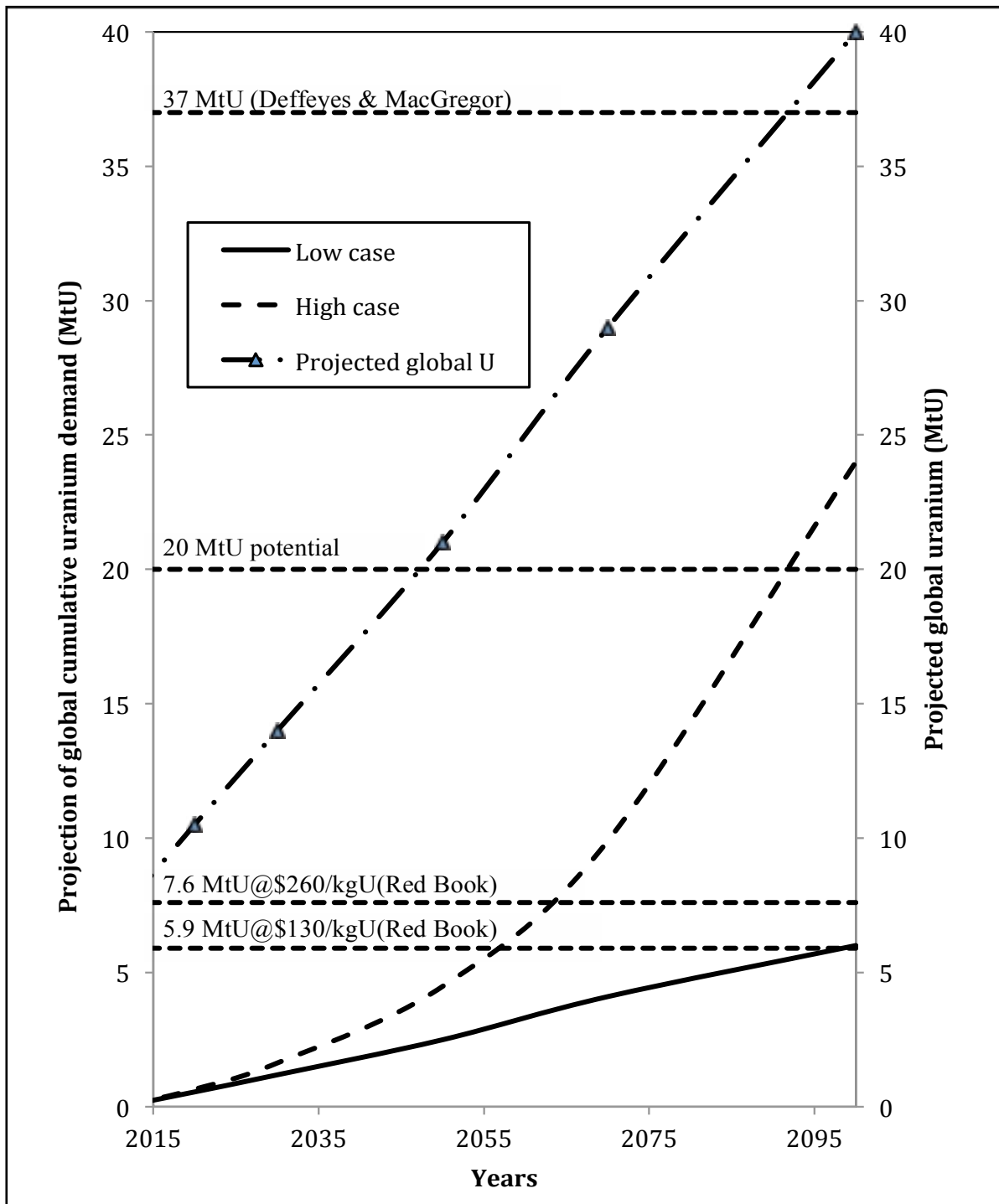
Note: Projection from 2012 to 2050 is based on IAEA report, and projection from 2050 to 2100 is based on our estimates.

How much uranium would be needed to feed that capacity assuming all is generated in a once-through cycle? We assume that the average installed reactor is a LWR with uranium consumption of roughly 173 tU/year from 2012 through 2020; and of roughly 150 tU/year from 2021 through 2100 (as discussed in Section II). Consequently, we estimate that by 2050 total consumption of uranium would be 2.5 MtU and 4.5 MtU for the low-growth and high-growth cases, respectively. And by 2100, total consumption of uranium would be 6 MtU and 24MtU, respectively (see Figure 5.4).

Hence the Red Book estimate of 7.6 MtU of identified uranium would be sufficient to meet demand generated under the IAEAs high-growth projection of global installed nuclear capacity through 2050, but not through 2100. A total requirement of 24 MtU by 2100 is also somewhat

¹⁰⁷ They are based on the average exponent growth rates from 2012 to 2050.

Figure 5.4: A Projection of Global Cumulative Uranium Demand (2015–2100)



higher than the 20 MtU estimated in Table 5.4. However, it is smaller than the 32 to 100 MtU given by equation A.1.

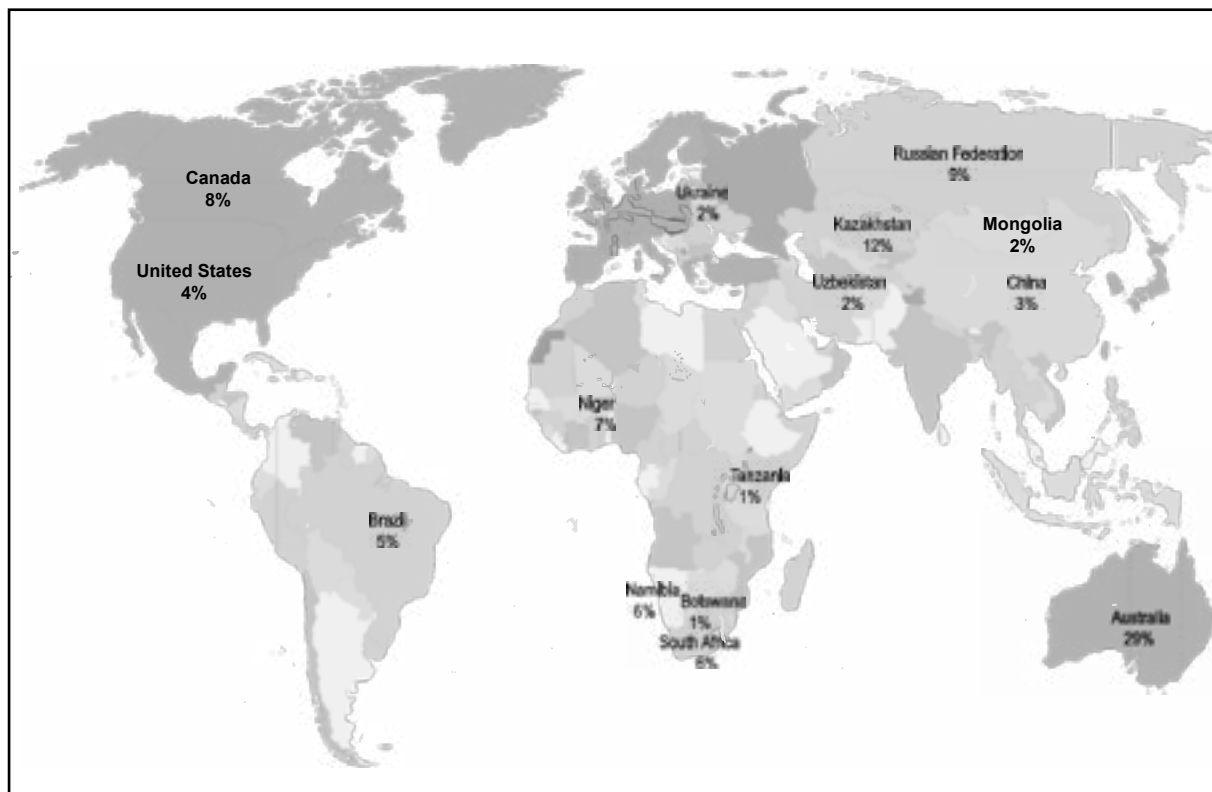
According to the Red Book data, global identified uranium increased from 4.7 MtU in 2004 to 7.6 MtU in 2012. If the world continues to spend on exploration at the same average rate as it did during the period between 2004 and 2012 yielding an average growth rate of 363 ktU/year), then by 2100, the total identified uranium would be around 40 MtU, as shown in Figure 5.4. This amount would be sufficient to meet demand generated under the IAEA's high-growth scenario through 2100.

Hence, global uranium resources are likely sufficient to supply even the highest growth scenarios for nuclear energy into the second half of the 21st century on a once-through cycle, and would last for the entire century except in cases involving very large growth of nuclear energy and modest growth of known uranium resources.

World Market for Uranium Resources

The Red Book 2014 estimates that total identified resources as of January 1, 2013 amounted to 5,902,900 tonnes of uranium metal (tU) in the <USD 130/kgU (<USD 50/lb U₃O₈) category, an increase of 10.8% compared to January 1, 2011. These resources are widely distributed among the 15 countries with more than a 1% share of total global identified resources available in this cost category; they share 97% of global identified resources (see Figure 5.5).

Figure 5.5: Global Distribution of Identified Resources (<USD 130/kgU)



Source: Red Book 2014; OECD-NEA and IAEA, *Uranium 2014: Resources, Production and Demand*.

Thus, unlike oil and natural gas resources which are distributed fairly unevenly in certain geographical locations, sources of uranium are diverse both geographically and politically, and collusion to raise prices and/or limit supplies would be unlikely. The widespread distribution of uranium resources is an important strategic aspect of nuclear energy considerations with respect to the security of energy supply.

Moreover, as shown in Table 5.5, the eight countries with more than a 5% share of total global identified resources available in the <USD 130/kgU price category account for around 82% of global identified resources. However, these eight countries' installed nuclear capacity totaled only 11% of total global installed nuclear capacity in 2012. This fact implies that the great powers in terms of uranium resources would have available for sale to others several times more uranium than required by domestic demand.

Table 5.5: Nuclear Power in States with Most Identified Uranium Resources

Country	Identified Resources at <USD 130/kgU (tU) (World Total 5,902,900 tU)	Share of World Total	Installed Nuclear Capacity (GWe net) (World Total 372 GWe)	Share of World Total
Australia	1,706,100	29%	0	0%
Kazakhstan	679,300	12%	0	0%
Russian Federation	505,900	9%	23.64	6.4%
Canada	493,900	8%	13.50	3.6%
Niger	404,900	7%	0	0%
Namibia	382,800	6%	0	0%
South Africa	338,100	6%	1.84	0.5%
Brazil	276,100	5%	1.88	0.5%
Total Share	4,840,400	82%	41	11%

On the other hand, as shown in Table 5.6, the 13 countries with more than a 1% share of total global installed nuclear capacity in 2012 accounted for around 90% of global capacity. Their uranium resources available in the <USD 130/kgU category account for only 26% of globally identified resources in this category. This means these nuclear power countries will need to buy uranium from the uranium producing countries—the uranium powers.

Hence the global distribution of uranium resources and nuclear power capacity can be generally characterized as “larger power group of nuclear energy has less uranium, larger power group of uranium has less nuclear energy.” Consequently, the trade in world uranium resources must constitute a natural world market.

If, as some Chinese experts have expressed concerns, geopolitics and foreign relations were to have a real impact on the global supply of uranium, China would not be the worst off under such conditions. First, some of the big powers in terms of uranium resources are members of

Table 5.6: Identified Uranium Resources in States with Most Installed Nuclear Capacity

Country	Installed Nuclear Capacity (GWe net) (World Total 372 GWe)	Share of World Total	Identified Resources at <USD 130/kgU (tU) (World Total 5,902,900 tU)	Share of World Total
United States	99.60	26.8%	207,400	4%
France	63.13	16.96%	0	0%
Japan	42.4	11.4%	6,600	0.1%
Russian Federation	23.64	6.4%	505,900	9%
South Korea	20.71	5.56%	0	0%
China	16.04	4.3%	199,100	3%
Canada	13.50	3.6%	493,900	8%
Ukraine	13.10	3.5%	117,700	2%
Germany	12.1	3.3%	0	0%
Sweden	9.5	2.55%	9,600	0.16%
United Kingdom	9.20	2.47%	0	0%
Spain	7.12	1.9%	0	0%
Belgium	5.927	1.59%	0	0%
Total Share	336	90.33%	1,550,100	26.26%

the Shanghai Cooperation Organization,¹⁰⁸ including China (3% of global uranium), Russia (9%) Kazakhstan (12%), Uzbekistan (2%), and Mongolia (as an observer, 2%). Second, other uranium powers, including Brazil (5%) and South Africa (6%), are members of the BRICS.¹⁰⁹ Third, China has traditional friendships with African countries such as Niger (7%) and Namibia (6%).

China has been in active collaboration with most of these uranium powers as discussed in Section IV. The uranium powers mentioned above account for 52% of global uranium in the <USD 130/kgU price category. However, they shared only around 11% of total nuclear capacity in 2012. Consequently, even under conditions of intensified geopolitical competition, Chinese access to foreign uranium will not deteriorate. Of course, given the fact that world uranium resources constitute a global market, political issues should not have a significant effect on the development of global uranium supplies.

Finally, some may argue that the situation of global uranium production in the near term could be different from that of global identified uranium resources. In practice, as shown in Table 5.7 and 5.8 the global production case has a similar mode as that of global identified uranium resources, and no significant changes for China. In particular, China has established good relations with many of those major producers in term of uranium exploration, mining and trading.

¹⁰⁸ The Shanghai Cooperation Organization or SCO or Shanghai Pact is a Eurasian political, economic and military organization which was founded in 2001 in Shanghai by the leaders of China, Kazakhstan, Kyrgyzstan, Russia, Tajikistan, and Uzbekistan. These countries, except for Uzbekistan, had been members of the Shanghai Five, founded in 1996; after the inclusion of Uzbekistan in 2001, the members renamed the organization (http://en.wikipedia.org/wiki/Shanghai_Cooperation_Organisation, accessed May 20, 2015).

¹⁰⁹ BRICS is the acronym for an association of five major emerging national economies: Brazil, Russia, India, China, and South Africa. The grouping was originally known as “BRIC” before the inclusion of South Africa in 2010. The BRICS members are all developing or newly industrialised countries, but they are distinguished by their large, fast-growing economies and significant influence on regional and global affairs; all five are G-20 members. <http://en.wikipedia.org/wiki/BRICS> (accessed May 20, 2015).

Table 5.7: Major Uranium Producers and Their Uranium Requirements in 2012

Country	Uranium Production (World Total: 58816 tU)	Share of World Total	Annual Reactor-Related Uranium Requirements (World Total: 61,600 tU)	Share of World Total
Kazakhstan	21,240	36%	0	0%
Canada	8,998	15%	1,600	2.6%
Australia	7,009	12%	0	0%
Niger	4,822	8%	0	0%
Namibia	4,653	8%	0	0%
Russian Federation	2,682	5%	3,800	6.2%
Uzbekistan	2,400	4%	0	0%
Total Share	51758	88%	5,400	8.8%

Table 5.8: Major Uranium Consumers and Their Uranium Production in 2012

Country	Annual Reactor-Related Uranium Requirements (World Total: 61,600 tU)	Share of World Total	Uranium Production (World Total: 58,816 tU)	Share of World Total
United States	23,085	37.5%	1,667	3%
France	8,000	13%	0	0%
South Korea	4,200	6.8%	0	0%
China	4,200	6.8%	1,450	2%
Russian Federation	3,800	6.2%	2,682	5%
Japan	1,960	3.2%	0	0%
Canada	1,600	2.6%	8,998	15%
Ukraine	2,480	4%	1,012	1.7%
Germany	2,000	3.2%	0	0%
Sweden	1,470	2.4%	0	0%
United Kingdom	1,220	2 %	686	1%
Belgium	1,030	1.7%	0	0%
Spain	940	1.5%	0	0%
Total Share	56,060	91%	16,470	28%

As the 2014 Red Book emphasizes, of the 30 countries currently using uranium in commercial NPPs, “...only Canada and South Africa produced enough uranium in 2012 to meet domestic requirements creating an uneven distribution between producing and consuming countries...all other countries with nuclear power must make use of imported uranium or secondary sources and, as a result, the international trade of uranium is a necessary and established aspect of the uranium market.” In practice, a fairly mature uranium market has been developed, with some 90% of volume being settled under long term contracts and 10% in the spot market, and several uranium brokerages are existing around the world (e.g., NUEXCO, TradeTech and UxC).

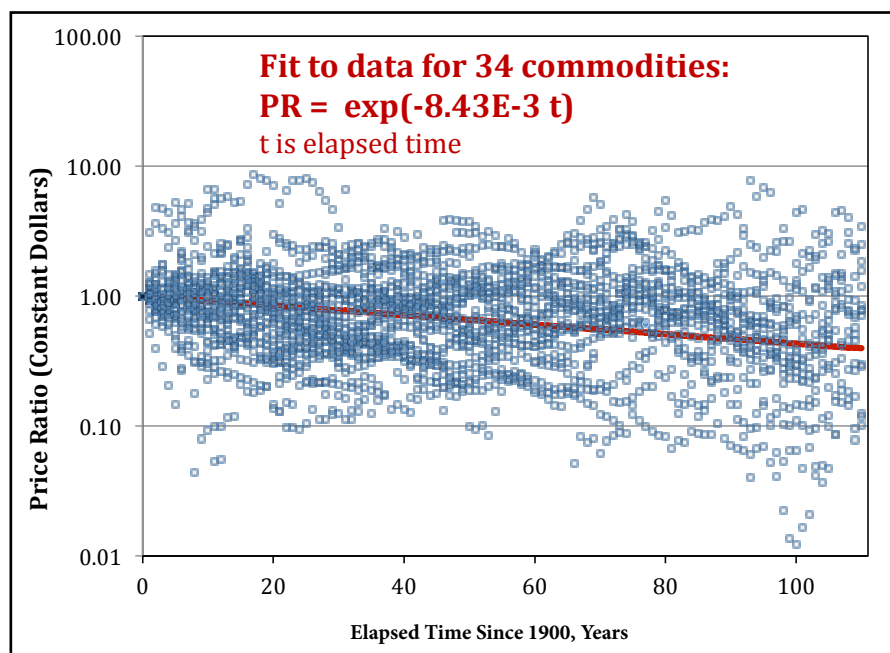
The Relatively Low Price of Uranium over the Long Run

Even though China may be able to access global uranium resources, even under heightened geopolitical competition, some Chinese experts worry that uranium prices could increase so abruptly in the future that the surge creates a supply crisis, rendering nuclear power operations uneconomical. The key questions raised by this hypothetical scenario are whether a dramatic, sustained increase in uranium prices is really plausible and whether the nuclear energy system is sensitive to sudden increases in the price of uranium.

It is difficult to predict longer-term prices. However, history has shown that past predictions of a steady rise have been proven wrong. The 2011 MIT study *The Future of the Nuclear Fuel Cycle*¹¹⁰ emphasizes that “there are good reasons to believe that even as demand increase the price of uranium will remain relatively low.” It estimates that if there were ten times as many plants worldwide and they operated for 100 years, the expected cost of producing uranium would increase by 50%. A probabilistic analysis carried out by the MIT authors considered the competing effects of technological learning, economies of scale, and depletion of highest-grade resources shifting mining operations to lower grade sources. The authors concluded that there was only a 10% chance that the uranium production cost would increase by more than a factor of three from its contemporary value.

Moreover, studies have shown that the prices of most other minerals have actually decreased (in constant dollars) over the past century as well as while cumulative quantities extracted have increased.¹¹¹ Figure 5.6 shows the twentieth-century price history obtained from U.S. Geological Survey data for over 30 elements. The price ratio is the current price of the element in each year

Figure 5.6: Price Ratio vs. Elapsed Time (Years)



Source: Erich Schneider, University of Texas, Austin.

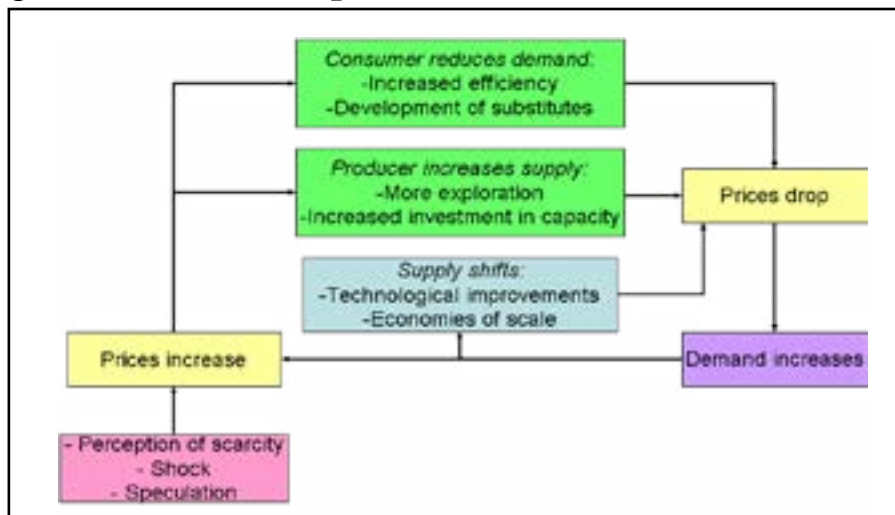
¹¹⁰ MIT, *The Future of the Nuclear Fuel Cycle*.

¹¹¹ Erich Schneider and William Sailor, “Long-term Uranium Supply Estimates,”; Kozimi and Moniz, *The Future of the Nuclear Fuel Cycle*.

divided by the price of the element in year 1 (1900 or the first year in which data is available). The figure implies that the prices of other elements have declined over the last century.

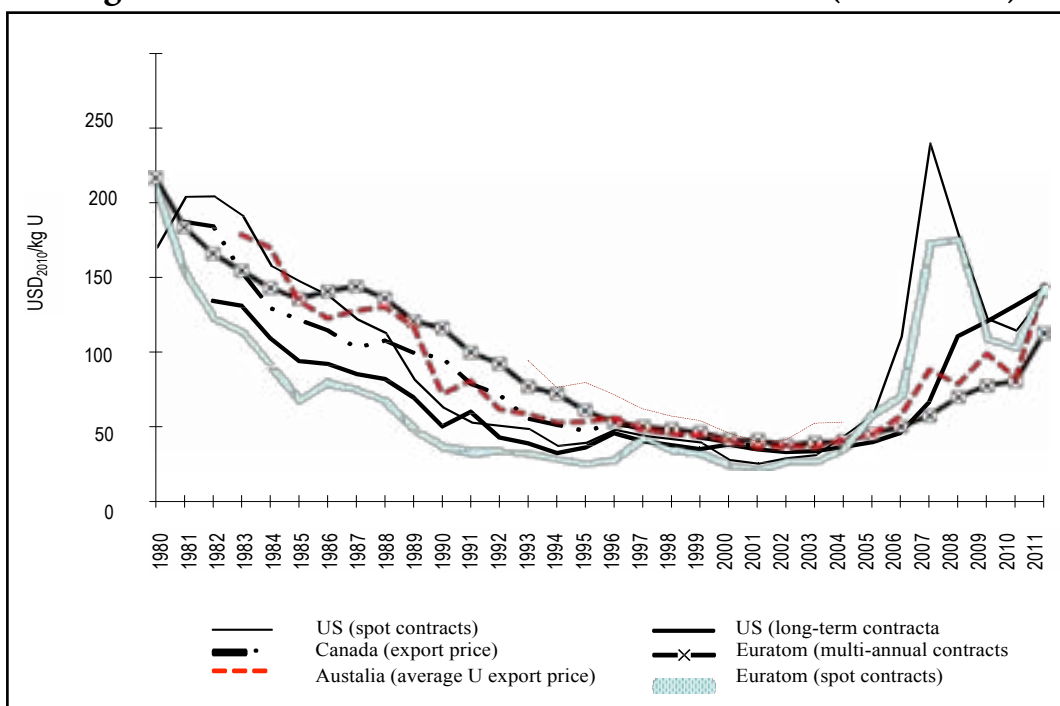
Past experience has shown that total known resources have increased faster than uranium has been depleted because of increases in exploration work and advances in technology. The amount of known uranium will likely increase with perceptions of scarcity and consequent price increases. Total world uranium resources are dynamic and related to commodity prices, meaning that with higher prices, the greater the level of exploitation and exploration, leading to greater availability.

Figure 5.7: Relationship of Uranium Prices with Other Factors



Source: Erich Schneider, “Uranium: Scarce or Sustainable?” presented at Harvard-Peking Workshop on Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011.

Figure 5.8: Evolution of Natural Uranium Prices (1980–2011)



Source: OECD-NEA, *Trends Towards Sustainability in the Nuclear Fuel Cycle*, Fig. 3.2, p. 66.

In practice, as shown in Figure 5.7, uranium prices are evolving dynamically to reflect changes in a number of factors including uranium demand, exploration and mining investment, technology advances, and measures to reduce demand. Uranium price increases will likely be incurred by factors including perceptions of uranium scarcity due to speculation, faster growth in nuclear power capacity, and increased demand at lower uranium prices. Once uranium prices increase, uranium producers will be encouraged to increase investments in exploration and mining and in improving technology, which will lead to recovery of more economically feasible uranium.

Meanwhile, consumers will take measures to reduce uranium demand, including by increasing efficiency and developing substitutes (e.g., other unconventional uranium resources). The net effect of these efforts will be to drive down uranium prices again. Then, another cycle of higher prices—lower prices—higher prices—lower prices will begin. Eventually, as history shows, these price cycles will lead to more resources being identified than the amount depleted.

Figure 5.8 shows historical uranium prices since 1980. Over the last four decades, the spot price experienced two peaks of over \$350 /kgU (in 2011 dollars) around 1977 and 2007 respectively, but it also declined to around \$68 /kgU in May 2014. In December 2014, it was at around \$90 /kgU. While the spot price has experienced some volatility since 2004, this typically affects less than 15% of all annual uranium transactions. The long-term price is relatively less-volatile and accounts for over 85% of all uranium deals.

Even if uranium prices were to see large increases, the busbar cost of nuclear electricity would not increase substantially as the cost of uranium accounts for only a small fraction of total nuclear electricity production costs. In the recent past, uranium has generally accounted for only about 2–4% of the lifetime-levelized busbar cost of nuclear-generated electricity. The situation is quite different for fossil fuel costs, which can account for up to 80% of fossil fuel electricity generation costs.¹¹² Table 5.9 shows the results of a MIT study on levelized costs for the once-through cycle.

**Table 5.9: The Levelized Cost of Electricity
for the Once-Through Cycle**

Cost Component	\$ Mil/kwh	Share (%)
Raw Uranium	2.76	3
Fuel Production (Conversion, Enrichment, and Fabrication)	4.35	5
Capital Charge	67.68	81
O&M Costs (Non-Fuel)	7.72	9
Back-end Fuel Cycle (Interim Storage and Ultimate Disposal)	1.3	2
Total LCOE	83.81	100

Source: MIT, *The Future of the Nuclear Fuel Cycle*.

¹¹² G. Pauluis and L. Van den Durpel, *Trends in the Nuclear Fuel Cycle: Economic, Environmental and Social Aspects*, OECD-NEA: Paris, 2001, <https://www.oecd-neo.org/nea-news/2001/trends19-2.pdf> (accessed April 29, 2015).

As the Table shows, assuming a uranium price of \$80/kg U, the contribution of raw uranium to the levelized cost of electricity (LCOE) is only 2.76 mill/kWh, or 3% of the total. This makes clear that savings on the purchase of raw uranium, given the minimal importance of the input price of uranium, will have little impact on the total cost of electricity.

Strategic Uranium Storage

If China became seriously concerned about the deterioration of its uranium supply, it could easily and inexpensively establish a ‘strategic’ uranium stockpile. One big advantage of nuclear power is the high energy density of its fuel. One tonne of uranium used in a LWR with an open fuel cycle (once-through) has the energy equivalent of 10,000–16,000 tonnes of oil or 14,000–23,000 tonnes of coal.¹¹³ Thus, uranium fuel is much easier to transport and store than fossil fuels.

Consider China’s Strategic Petroleum Resources (SPR) program which, by 2015/2016, is to have a total capacity of approximately 500 million barrels (or 80 days of imports¹¹⁴) (see Box 5.1). Assuming the price of imported oil is about \$50/bbl, then the SPR of 500 million barrels has a value of \$25 billion. Assuming a 1 GWe PWR requires 150 tU/ year as discussed previously and the price of natural uranium is at \$100 /kgU, then the same investment in natural uranium would support 60 1 GWe PWRs (China officially plans to have 58 GWe by 2020) for about 30 years.

To support a strategic uranium storage program, China’s government could establish a “Strategic Uranium Reserve” fund in the same way it established a “Spent Fuel Management Fund” in 2010.¹¹⁵ In that year, the government began collecting monies for the fund at a rate of ¥0.026 / kWh (around 4.3 mill /kWh) for commercial PWRs that had been in operation for at least five years (except for the two CANDU reactors, all other commercial reactors running or under construction are PWRs).

The proceeds of the fund are used to pay for:

- Spent fuel shipments (e.g., since 2003, spent fuel from Daya Bay has been shipped to spent storage pools at the pilot reprocessing plant);
- Sway-from-reactor storage;
- Spent fuel reprocessing at the pilot reprocessing facility (the pilot plant has been in operation since 2010);
- Commercial reprocessing plant activities such as construction, operation, improvement, and decommissioning; and
- Other fees for spent fuel management and disposal.

¹¹³ OECD-NEA, *Trends towards Sustainability in the Nuclear Fuel Cycle*.

¹¹⁴ In 2014, China consumed about 11 million barrels per day and about 4.5 million barrels was from domestic production which indicated China imported about 6.5 mbd. Thus a reserve of 500 million barrels is about 80 days of imports at 2014 level.

¹¹⁵ Ministry of Finance, the National Development and Reform Commission, and Ministry of Industry and Information Technology, “Nuclear power plant spent fuel management fund levy and use: interim measures,” (in Chinese), July 12, 2010, http://www.mof.gov.cn/zhengwuxinxi/caizhengwengao/2010nianwengao/wengao6/201009/t20100903_337280.html (accessed May 6, 2015).

Assuming the government begins collecting monies for a “strategic uranium reserve” fund at 1.4 mil/kWh (about one-third the rate that maintains the spent fuel fund), which is equivalent to about 1.5% of nuclear electricity production costs (around \$0.93/kWh in China), then one 1 GWe PWR with a capacity factor of 85% would pay into the fund around \$10 million a year. This sum could buy 100 tU at a price of \$100/kgU. Assuming a 1 GWe PWR requires 150 tU per year after 2020, then a contribution collected every three years from each PWR would be enough to buy uranium resources to support another two years of operations for that PWR. This means a fund drawing from a fleet of 60 1 GWe PWRs for 30 years would be sufficient to support a 20-year supply of uranium for those reactors.

In fact, since 2011 a strategic uranium storage plan has been under consideration as a national energy project in the Twelfth Five Year Energy Plan.¹¹⁶ CNNC formally established in March 2011 China’s first dedicated bonded storehouse for nuclear fuel at its Plant 404, which is managed by its subsidiary, CNEIC. The facility will provide convenient bonded arrangements for CNNC to acquire foreign uranium resources and secure China’s energy security. However, it does not actively work.

Finally, reducing the tails assay in enrichment can save natural uranium but will increase SWU requirements. There is always a trade-off between the cost of enrichment SWUs and the cost of uranium. For instance, producing one kilogram of LEU product enriched to 5% (w/o) will require 10.30 kg and 8.02 kg of natural uranium for tails at 0.25 (w/o) and 0.10 (w/o), respectively. This means the uranium requirement is reduced by about 22% when tails are reduced from 0.25 to 0.10. However, this is offset by an increase in SWUs needed to enrich the uranium, in proportion to the increase from 7.92 kg to 11.99 kg—or 51%. Assume the price of natural uranium is about \$92/kgU, conversion costs are \$8/kgU, and the SWU cost is about \$88/kg. Thus, the savings from reduced costs for uranium purchases and uranium conversion is about equal to \$228. The increase in costs due to the additional SWUs required is \$358. Hence, at current prices for uranium purchases, conversion, and SWUs, it is not economically feasible to take the route of reducing tails. However, as the price of uranium increases and the cost per SWU decreases, this option could become more favorable. Such a trend can be expected as centrifuge enrichment technology advances and incorporates new innovations.

Given that China’s nuclear industry currently maintains self-sufficiency in the supply of conversion and enrichments services, even if Chinese operators of enrichment plants do not want to pursue lower tail assays at this moment, all those tails with higher assays remain their assets. In other words, these tails would be one part of China’s stockpile of uranium resources. Thus, saving 20% of enriched natural uranium by reducing tails option would increase total uranium resources from domestic and foreign sources from 800 ktU to around 1000 ktU, which would be enough to meet demand in 2050 even under the high-growth scenario discussed previously (i.e., 400 GWe of generating capacity in 2050).

¹¹⁶ National Energy Administration, *National Energy and Technology Plan during the 12th Five-Year Period (2011–2015)* (in Chinese), November, 2011, http://www.nea.gov.cn/131398352_11n.pdf (accessed May 15, 2015)

China's Strategic Petroleum Resources Program

Since 1993 China has become a net oil importer. China is currently the world's second-largest oil consumer behind the United States, and has been the world's second-largest net importer of crude oil and petroleum products since 2009. The U.S. Energy Information Agency (EIA) projects that China will surpass the United States as the largest net oil importer by 2014.¹ As China's 2012 energy white paper stated, "the percentage of imported petroleum in the total petroleum consumption has risen from 32% at the beginning of the 21st century to the present 57%."² The government's current Five-Year Plan targets an oil import ceiling of no more than 61% of demand by the end of 2015. The EIA expects China to import over 66% of its total oil by 2020 and 72% by 2040.³ The Chinese government has expressed concerns that "marine transportation of petroleum and cross-border pipeline transmission of oil and gas face ever-greater security risks. Price fluctuations in the international energy market make it more difficult to guarantee domestic energy supply."⁴

Concerned about security of oil supply, China has worked on an official Strategic Petroleum Resources (SPR) program since 2001. China aims to follow the International Energy Agency standard on holding crude oil stockpiles equivalent to 90 days of net petroleum imports.⁵ The main goal of the SPR program is to reduce the impact of a crude oil supply disruption. China's National Energy Administration, under the National Development and Reform Commission (NDRC), is in charge of the country's SPR. The SPR is being constructed in three phases: Phase I: completed in 2004–2009, it established an initial total capacity of 102 million barrels; Phase II: Construction began in late 2008, with completion foreseen by 2014, to add an additional capacity of 169 million barrels; Phase III: the last phase will build an additional 229 million barrels of capacity. Thus, the three-phase program will create a total SPR capacity of about 500 million barrels.

¹ U.S. Energy Information Agency. "China—Analysis," last modified February 4, 2014, <http://www.eia.gov/countries/cab.cfm?fips=ch> (accessed May 3, 2015).

² The Information Office of the State Council, China's Energy Policy 2012 (in Chinese).

³ U.S. Energy Information Agency. "China—Analysis."

⁴ The Information Office of the State Council, China's Energy Policy 2012.

⁵ Y. Bai, C.A. Dahl, D.Q. Zhou, and P. Zhou, "Stockpile Strategy for China's Emergency Oil Reserve: A Dynamic Programming Approach," *Energy Policy*, Vol. 73 (October 2014), p. 12–20.

VI: Recommendations

To secure a stable supply of uranium for China's long-term nuclear power development, China needs to intensify its investments continually in prospecting, exploration, and mining in domestic regions, and adopt a strategy for exploitation of foreign deposits, world trade, and uranium stockpiling. In the past, China's uranium exploration activities have experienced "up and down" periods, mainly due to inconsistent nuclear power plans over time. China lacked a long-term, centrally designed strategy (i.e., a comprehensive national nuclear power plan) for nuclear power development for the last three decades. The role of nuclear power in the nation's energy system has since swung from being "supplemental" to "major," which heavily affected the government's and industry's efforts in uranium-related work as shown in Figure 3.1. The central government should have a long-term and comprehensive national nuclear power development plan, and accordingly have a long-term uranium acquisition plan.

To secure long-term uranium supplies for its fast-growing nuclear power industry, the central government should take a number of measures to intensify uranium exploration and mining, both domestic and abroad, continue participation in international trading of uranium, and adopt a strategy to provide for the storage of uranium. Specifically, it should consider the recommendations discussed below.

Intensifying Domestic Exploration

As shown in Figure 3.2, since the mid-2000s China has significantly increased its investments in uranium exploration. Consequently, China has almost tripled its uranium resources over the last decade. China still has space to increase its investments, in terms of both drilling and expenditures. While China increased its drilling footage to about 920 km in 2012, it is only at about 60% of the peak drilling distance of 1,550 km achieved in 1978. Moreover, even though China has increased its expenditures on drilling efforts, this investment is equal to only 1.25% of total funds invested in the whole field of solid minerals exploration. To identify more uranium resources, the government needs to do more, including:

- The government should have a long-term, stable, and effective strategic plan for its uranium industry, and should consider how to best integrate this plan into its broader nuclear energy plan.
- The government should encourage more players (beyond the currently dominant CNNC) to enter the uranium exploration and mining industry, and should create a mechanism for competition among those players. It should also coordinate among both players in the uranium industry and firms in other metal minerals businesses to avoid wastage of uranium resources.
- Besides increasing its financial support, the government should also encourage other social actors to participate in investing in uranium-related activities. Moreover, China should establish a dedicated fund for uranium activities.

- The state should invest more to improve estimates of the country's uranium potential by developing and applying new appraisal and prediction methods. The effort should focus on prospecting and exploration work in those areas which have been surveyed to very low detail or have never been covered, exploration work beyond depths of 500 meters and 1000 meters, and areas surrounding known uranium belts and deposits.
- The state should increase efforts to identify more uranium resources, including by focusing on uranium prospecting and exploration in the northern China regions with uranium deposits suitable for *in situ* leaching. It should also seek to expand discoveries of vein-type uranium deposits related to volcanic rock and granite in southern China, speed up identification of medium- and large-scale deposits, and increase minable uranium resources.
- The government should increase R&D investment in certain areas, including uranium mineralization theory and models, exploration technology and physical detection equipment, and production and processing methods for mining uranium. Moreover, it should increase R&D on unconventional uranium resources (e.g., phosphate deposits) and extraction of uranium from sea water.
- The state should strengthen training programs and encourage the training of more professional and technical personnel for uranium work, and improve the integration of human resources capabilities in the industry.

Strengthening Overseas Exploration

There are plenty of uranium resources distributed globally. By its nature, the global uranium market is open and competitive. China should adhere to a policy of “going out” to secure more foreign uranium supplies. To effectively implement this policy, the government should take the following measures:

- The government should establish a dedicated state organization or council to implement its strategy for the acquisition of uranium abroad. It should unify management and guidance for Chinese companies' engaging in uranium work abroad, including in the areas of project selection, financing, technology, training, and foreign affairs. Also the new organization should be responsible for coordinating cooperation among Chinese companies themselves and between Chinese companies and foreign countries or companies.
- The government should support (in financing and policy) its companies to enhance their competitive capacity in global exploration and mining activities. Chinese companies are relative new-comers in this field and are short of money, compared to the experienced, large uranium companies, such as Canada's Cameco, France's AREVA, Australia's Rio Tinto, and South Africa's AngloGold, which collectively already control many of the most favorable uranium deposits around the world. Government support can take the form of financial investment, low-rate loans, and tax incentives for uranium work abroad. The state should also establish a foreign uranium development fund targeting exploration and mining of identified uranium resources.

- China should strengthen its regulations on uranium activities abroad, including laws on insurance of overseas investments in uranium exploration and mining. Also, to facilitate cooperation with foreign countries, China should take measures to assure them that imported uranium is accountable and only to be used for civilian purposes.
- The government should increase investments in training professionals for the international uranium business, and on developing advanced technology and equipment for uranium work abroad.

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@harvard.edu

Website: <http://belfercenter.org>

Copyright 2015 President and Fellows of Harvard College