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Project on Managing the Atom

The Cost of Reprocessing in China

Matthew Bunn
Hui Zhang
Li Kang



HARVARD Kennedy School
Belfer Center for Science and International Affairs

January 2016

Project on Managing the Atom
Report

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Background: Satellite imagery of the Jiuquan Nuclear Complex (Plant 404), August 31, 2007 (DigitalGlobe and Google Earth)
Inset: The spent fuel pool inside the pilot reprocessing plant, at the Jiuquan nuclear complex in China. Source: Zhang Donghui, "Status of China National SFR Program" (presentation, International Workshop on Prevention and Mitigation of Severe Accidents in Sodium-Cooled Fast Reactors, Tsuruga, Japan, June 12–13, 2012).

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Project on Managing the Atom

The Cost of Reprocessing in China

Matthew Bunn
Hui Zhang
Li Kang



HARVARD Kennedy School
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January 2016

Preface

This study is part of a series of reports the Project on Managing the Atom has produced on China's nuclear future, particularly management of nuclear material and the nuclear fuel cycle. Other reports in the series have focused, respectively, on China's access to uranium resources, China's uranium enrichment capacity, and China's efforts to secure its nuclear weapons, materials, and facilities. In this report, we focus on the question of reprocessing spent nuclear fuel in China, examining in particular how much electing to reprocess that fuel might cost.

In writing this report, Li Kang made a major contribution to Chapter 3, in particular, using engineering extrapolations from China's existing 50 tons heavy metal per year pilot plant to estimate costs of larger reprocessing plants. The remainder of the report was largely written by Matthew Bunn and Hui Zhang, and Li Kang should not be held responsible for the arguments those chapters contain.

A number of Chinese nuclear experts and officials granted interviews during the preparation of this report. As the topic of the report involves ongoing commercial negotiations and political decision-making, we express our gratitude for their insights without identifying them by name. Our work on this report benefited from a series of workshops the Belfer Center's Managing the Atom Project co-convened with colleagues at Tsinghua University and Peking University, respectively in Beijing, and with the China Arms Control and Disarmament Association in Shenzhen, China. We thank Li Bin, Du Xianwan, Wang Yugang, and Li Hong for their generous hospitality and for hosting the respective workshops. We thank the participants in those workshops for their insights. We would also would like to thank Mike Ehinger, Richard Garwin, Mark Hibbs, Martin Malin, Erich Schneider, Gordon Thompson, William Tobey, and Frank von Hippel for their participation in workshops and helpful comments and suggestions. We also thank Yun Zhou for her help on early drafts of this paper. We thank our colleagues Joshua Anderson, Bobby Kim, Katherine Miller, and Nate Sans for help with 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.

Matthew Bunn, Hui Zhang, and Li Kang
January 2016

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Matthew Bunn is a Professor of Practice at Harvard's Kennedy School and Co-Principal Investigator of the Project on Managing the Atom. His research interests include nuclear theft and terrorism; nuclear proliferation and measures to control it; the future of nuclear energy and its fuel cycle; and innovation in energy technologies. Before coming to Harvard, Bunn served as an adviser to the White House Office of Science and Technology Policy, as a study director at the National Academy of Sciences, and as editor of *Arms Control Today*. He is the author or co-author of more than 20 books or major technical reports (most recently *Transforming U.S. Energy Innovation*), and over a hundred articles in publications ranging from *Science* to *The Washington Post*. He was recently a member of the Committee on International Security and Arms Control of the National Academies and the Department of Energy's Nuclear Energy Advisory Committee. He is an elected Fellow of the American Association for the Advancement of Science and a recipient of the Federation of American Scientists' Hans Bethe award for science and security and the American Physical Society's Joseph A. Burton Forum award for his work on nuclear security.

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

Li Kang is a senior engineer with China Nuclear Power Engineering Co., Ltd (CNPE) and deputy director of the Economic Evaluation Division of the Institute of Engineering Economics within the China National Nuclear Corporation. He received a bachelor's degree in computer science from Guizhou University in 1996, a master's degree in Information Sciences from the Institute of Scientific and Technical Information of China in 2006, and a Ph.D in Technical Economics and Management from Renmin University of China in 2014. He has worked at CNPE since 1996. He has been involved in a number of projects on cost estimates for constructing nuclear facilities including power reactors and reprocessing facilities, and taken a lead on some of them. He has also co-edited policy documents and regulations related to the cost of nuclear power plant construction.

Table of Contents

Executive Summary 1

1. Introduction 7

2. China's Reprocessing and Recycling: Status and Plans 9

2.1 China's Closed Fuel Cycle Policy 9

2.2 China's Nuclear Power Plans 12

2.3 Spent Fuel Storage 14

2.4 China's Civilian Reprocessing Pilot Plant 20

2.5 Proposals for an 800 tHM/yr Commercial Reprocessing Plant 26

2.6 Proposals for a 200 tHM/yr Demonstration Reprocessing Plant and MOX Fuel Fabrication Plant 28

2.7 China's Experimental Fast Reactor 28

2.8 Proposals for Fast Breeder Reactors in China 32

3. The Cost of Reprocessing: China's Experience & Projections 35

3.1 The Cost of China's Pilot Reprocessing Plant 35

3.2 Chinese Estimates of the Capital Costs of Larger Reprocessing Plants 37

3.2.1 Projected Capital Costs for a 200 tHM/yr Reprocessing Plant *37*

3.2.2 Projected Capital Costs for an 800 tHM/yr Reprocessing Plant *39*

3.2.3 Uncertainties of the Scaling Approach *40*

3.3 Capital Cost of the China Experimental Fast Reactor 41

4. The Cost of Reprocessing: International Experience 43

4.1 The Rokkasho Reprocessing Plant 44

4.2 The Thermal Oxide Reprocessing Plant 46

4.3 UP2-800 and UP3 49

4.4 Would China's Experience Likely Be More Like Rokkasho, or Like THORP and La Hague? 51

5. Projecting Unit Costs of Reprocessing in China 53

5.1 High and Low Estimates of Capital and Operating Costs 54

5.2 Financing a Reprocessing Plant in China and the Unit Cost of Reprocessing 55

6. Potential Costs of Once-Through and Recycling Fuel Cycles in China 61

7. The Right Reprocessing Approach? China's Potential for Leapfrogging 67

7.1 Supporting China's Near-Term Fuel Cycle Plans 67

7.2 Supporting China's Long-Term Fuel Cycle Ambitions 68

7.3 Non-Economic Costs to Be Considered 69

8. Conclusions and Recommendations 71

Appendix 1: The Effect of Currency Exchange Rates and Inflation 75

Appendix 2: Recent International Projections of Reprocessing Costs 79



Satellite imagery of the Jiuquan Nuclear Complex (Plant 404), August 31, 2007

DigitalGlobe and Google Earth

Executive Summary

As it expands its fleet of nuclear power plants, China faces an important decision: whether to make large capital investments in facilities to reprocess spent nuclear fuel and recycle the resulting plutonium in fast-neutron reactors, or continue to store nuclear fuel, leaving for the future decisions on whether to reprocess the fuel or dispose of it as waste. This report summarizes estimates of the cost of current proposals for building and operating reprocessing plants and fast reactors in China.

China has been considering both a reprocessing plant designed to reprocess 200 metric tons of heavy metal in spent fuel each year (200 tHM/yr) and one designed to process 800 tHM/yr. Both indigenous Chinese technology and purchase of a large reprocessing plant from France are being considered. At the same time, China is considering construction of a demonstration fast reactor and a commercial fast reactor. There, too, both indigenous Chinese technology and a purchase from abroad (in this case from Russia) have been considered. The background of China's program and the facilities being considered are described in Chapters 1 and 2.

Using engineering extrapolations from China's existing 50 tHM/yr pilot plant, Chinese experts estimate that the cost of a 200 tHM/yr reprocessing plant using indigenous Chinese technology might be in the range of $3.2 billion (2014 $). By the same method, the cost of an 800 tHM/yr plant would be over $9 billion. These estimates are described in Chapter 3.

Because of the uncertainties of extrapolating from the pilot plant experience, it is worth examining international experience as well. The costs of the French and British reprocessing plants, built long ago, are comparable to the estimates based on extrapolating from the pilot plant. The more recent experiences with the Japanese reprocessing plant at Rokkasho (with a capital cost of over $20 billion, many times the original estimate) and the U.S. plutonium-uranium mixed oxide (MOX) fuel fabrication plant (with a capital cost of over $7 billion, again many times the original estimate) suggest much higher costs. The €20 billion price Areva has reportedly offered for the proposed 800 tHM/yr plant suggests that they believe costs for a Chinese plant will be closer to the Japanese experience than to the old French experience. These estimates are discussed in Chapter 4.

Based on these estimates and this international experience, Table ES.1 shows high and low estimates for the cost of building and operating a 200 tHM/yr reprocessing plant and an 800 tHM/yr reprocessing plant. Even the low estimates range from four to seven times the cost of storing the same fuel for 40 years, amounting to savings ranging from over $9 billion to over $70 billion. Hence, if China chooses not to invest in large reprocessing plants over the next several decades, it would have billions of dollars in unspent funds available that could be used to build more nuclear power plants to provide additional clean electricity for China's economy.

Table ES.1: **High and Low Estimates of Reprocessing Capital and Operating Costs**

Plant	**Capital cost**	**Operating cost**	**40-year cost** (no financing)	**40-year dry storage cost**
200 tHM/yr, Low	$3.20 B	$0.19 B	$10.80 B	$1.60 B
200 tHM/yr, High	$5.70 B	$0.34 B	$19.30 B	$1.60 B
800 tHM/yr, Low	$8.00 B	$0.48 B	$27.20 B	$6.40 B
800 tHM/yr High	$20.00 B	$1.50 B	$80.00 B	$6.40 B

The costs in Table ES.1 do not include financing costs, which are a crucial part of the costs of reprocessing. Even if commercial reprocessing plants were partly government-financed, there would be borrowing costs, and the opportunity costs of not investing those funds elsewhere in the Chinese economy have to be considered. At a low, government-supported financing rate of 3 percent, with no taxes or insurance considered, the per-kilogram reprocessing cost for the low cost estimate for the 800 tHM/yr plant would be in the range of $1,400/kgHM, far higher than the costs of dry storage followed by direct disposal. For the high cost estimate for the 800 tHM/yr plant, with the same low 3 percent financing, the cost would be some $4,000/kgHM. For the smaller plant at 3 percent financing, costs would range from $2,300/kgHM for the low estimate up to some $4,000/kgHM for the high estimate. Costs for privately financed facilities would drive per-kilogram prices still higher. Per-kilogram costs of reprocessing are discussed in Chapter 5.

Even with assumptions on fuel cycle costs quite favorable to reprocessing, reprocessing at a $1400/kgHM cost and recycling the plutonium in existing LWRs would increase the cost of the nuclear fuel cycle by roughly two-thirds. The impact on the overall cost of nuclear energy would be more modest, however, as that cost is dominated by the capital cost of the reactors.

China does not plan to recycle plutonium in LWRs, however, but in fast-neutron reactors. Most analysts expect such reactors to have capital costs 20–50 percent higher than those of LWRs, along with higher fuel cycle and operations and maintenance costs. Overall, a shift to such reactors, with reprocessing, might increase the cost of nuclear energy by 20–50 percent. These estimates of full fuel cycle costs are discussed in Chapter 6.

The planned 200 tHM/yr reprocessing plant and the proposed 800 tHM/yr plant may not be the best facilities for supporting China's near-term and long-term fuel cycle plans. Fast reactors could be started up with enriched uranium or with plutonium imported from other countries which have large excess stocks available, at far lower cost than building these proposed reprocessing plants. To demonstrate the potential of a closed fuel cycle, China would ultimately need reprocessing plants and plutonium fuel fabrication plants designed to handle fast reactor fuel, rather than LWR fuel. Over the longer term, establishing a leadership role for China in fuel processing technology might be better accomplished at lower cost by building a flexible R&D facility to explore a variety of new concepts than by investing in commercial-scale facilities based on decades-old technologies.

China should also consider the non-economic costs of near-term investment in reprocessing plants. Such facilities will focus the efforts of a substantial number of nuclear experts, for design, construction, operation, and regulation, at a time when providing qualified personnel for the rapid growth of nuclear energy in China is posing major challenges. Chinese nuclear regulatory agencies face particular challenges, and would have to acquire a wide range of expertise in areas quite different from those needed for nuclear reactor regulation to effectively regulate large reprocessing and plutonium fuel fabrication facilities. These issues are addressed in Chapter 7.

Fundamentally, we conclude that investing in large reprocessing facilities in the near term would be much more expensive for China than the alternatives. China has the luxury of time, as it has access to plenty of uranium to fuel its nuclear growth for decades to come, and dry casks can provide a safe, secure, and cost-effective way of managing spent fuel for many decades, leaving all options open for the future.

We recommend that China take the following steps:

- Undertake a comprehensive review of the economic, safety, security, nonproliferation, and waste-management benefits and risks of near-term construction of reprocessing plants and breeder reactors versus those of continuing to store spent nuclear fuel for

several decades. Ultimately, China should choose the option that brings the best balance of costs, risks, and benefits.

- Invest in both at-reactor and centralized dry cask storage facilities, which offer important flexibility for any fuel cycle option chosen.
- Set aside funds for spent fuel management in risk-free accounts, ensuring that funds will be available in the future to implement whatever spent fuel management approaches are ultimately chosen.
- Keep in mind, in making decisions, that early cost estimates are likely to grow, and approve major reprocessing and breeder reactor projects only if they would still be worthwhile if the cost were 2–3 times higher than the early estimates (and the schedules substantially longer).
- Avoid technological and institutional lock-in on one approach to the extent practicable, maintaining flexibility to adapt to future developments.
- Pursue R&D on fuel-cycle technologies, intended to put China in a leadership role in these technologies.
- Ensure that the potential nuclear proliferation impacts of China's choices—and in particular how China's choices may effect the spread of reprocessing technologies in non-nuclear-weapon states—are fully considered in choosing the best option for China.
- Ensure that the chosen approach is implemented in a way that meets the highest standards of safety, security, safeguards, and waste management (specifics of this and other recommendations are discussed in Chapter 8).

China has the world's largest nuclear construction program, and within a couple of decades, China is likely to have the largest number of nuclear power plants in the world. China is already becoming one of the world leaders in nuclear energy technology, and has every reason to seek to maintain and strengthen that leadership role. Pursuing the safest, most secure, and most cost-effective approaches available today—while pursuing a vigorous R&D program on new approaches for the future—is likely to be the best way to promote China's nuclear energy leadership.



A containment dome is lifted and installed at the Haiyang Nuclear Power Plant in Haiyang, China, September 12, 2015.

Tang Ke, Imagechina/AP

1. Introduction

China is making major investments in nuclear energy to reduce its carbon emissions, the air pollution from coal-fired electricity, and its dependence on coal and other fossil fuels. China is building more nuclear power reactors than any other country on earth. As of November 2015, China had 31 power reactors (28.5 gigawatts-electric, or GWe) in operation with 21 units under construction (23.4 GWe).[1] In October 2012, China's State Council announced new, post-Fukushima targets for nuclear power plant construction, calling for an installed capacity of 58 GWe by 2020, with another 30 GWe under construction by that time.[2] China will issue its 13th Five-Year Plan next year. Chinese reports suggest that the country will maintain the target of 58 GWe in operation and 30 GWe under construction by 2020. Many more reactors are under consideration for construction in the coming decades. Within a few decades, China is expected to operate more nuclear power plants than any other country in the world. Nuclear energy will be a central element of meeting Chinese President Xi Jinping's 2014 commitment to produce 20 percent of Chinese primary energy from low-carbon sources by 2030.[3]

For decades, China has planned to reprocess the spent fuel from nuclear power plants to recover and recycle the plutonium and uranium.[4] Today, China is in the midst of deciding whether to move forward in the near term on building a commercial-scale reprocessing plant and two commercial-scale fast-neutron breeder reactors. The alternative would be to store spent fuel for the time being and defer decisions on reprocessing for the future, potentially investing the resources that would otherwise go to the reprocessing plant and breeder reactors in providing additional low-carbon energy (including additional nuclear reactors) instead.

1 International Atomic Energy Agency, "People's Republic of China," *Power Reactor Information System*, https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=CN (accessed January 4, 2016).

2 The State Council of the People's Republic of China, Energy Development Strategy Action Plan (2014-2020) (Beijing: State Council, June 2014), http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm (accessed January 4, 2016).

3 The White House, Office of the Press Secretary, "U.S.-China Joint Announcement on Climate Change," November 11, 2014, http://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change (accessed January 4, 2016).

4 For discussions of these plans and their rationale, see Xu Mi, "Fast Reactor Development Strategy Targets Study in China," *Chinese Journal of Nuclear Science and Engineering* 28, no. 1 (2008): 20-25; Xu Mi, "Fast Reactor Development for a Sustainable Nuclear Energy Supply in China" (presentation, Harvard-Tsinghua Workshop on Nuclear Energy and Nuclear Security, Beijing, China, March 14–15, 2010); Gu Zhongmao, "The Sustainable Nuclear Energy Needs Closed Fuel Cycle" (presentation, Harvard-Peking University Workshop on the Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011).

Many factors will be considered in this decision. One important factor—the subject of this report—is cost. How much would it cost China to reprocess its spent fuel? How much would it cost to store the spent fuel instead? How much would the full fuel cycle for each of these approaches cost?

There are substantial uncertainties in answering these questions, as China does not yet have experience in building and operating comparable facilities on comparable scales, and international experience is limited and has varied significantly from one country to another. Nevertheless, much can be learned from China's experience with its smaller pilot-scale reprocessing facility and from experience with large commercial reprocessing plants in other countries. Estimates based on these experiences, developed in this report, can help inform China's decision-making process.

This report proceeds as follows. Chapter 2 describes China's nuclear energy plans and the reprocessing and fast-reactor options currently being considered. Chapter 3 describes China's experience with the costs of the pilot-scale reprocessing plant and offers cost estimates based on extrapolating from that experience to larger facilities. Chapter 4 describes experiences with the cost of large-scale reprocessing plants in other countries and what might be learned from those experiences—including a discussion of how construction and operating costs in China might vary from those in other countries, based on the relative costs of somewhat analogous facilities, such as large chemical plants or nuclear power reactors. Chapter 5 outlines what these cost estimates suggest for the likely per-kilogram costs of reprocessing at a large-scale facility in China. Chapter 6 provides a preliminary assessment of the likely costs of a fuel cycle based on storage and disposal of spent fuel in China for the next few decades versus the likely costs of fuel cycles based on reprocessing and recycling, either in thermal reactors or in fast reactors. Chapter 7 explores whether the reprocessing plants currently envisioned are the best approach to supporting China's fuel cycle plans. Chapter 8 offers conclusions and recommendations. Two appendices explore uncertainties that arise in comparing costs from different countries at different times, and other estimates of the costs of reprocessing that have appeared in the published literature in recent times.

2. China's Reprocessing and Recycling: Status and Plans

China has long had a policy of eventually closing the nuclear fuel cycle by building plutonium reprocessing plants and fast-neutron "breeder" reactors to use the resulting plutonium and produce more. Although China maintains a closed fuel cycle policy, it has not yet committed funds to construction of commercial-scale reprocessing plants or fast-neutron reactors.

2.1 China's Closed Fuel Cycle Policy

Since 1983, China has maintained its closed fuel cycle policy, but without yet building more than pilot-scale facilities to implement it. According to its proponents, the major benefits of this policy will be full utilization of the energy in China's uranium resources, a drastic reduction in the required volume for radioactive waste in a deep underground repository, and a path forward for the spent fuel accumulating in China's reactor pools.[5]

In 1978, China began to prioritize its economic reform and, as a result, China's nuclear industry began to shift from a primarily military focus to a civilian one. Chinese leader Deng Xiaoping decided to buy early civilian nuclear reactors from the French, and after three years of negotiation, the Daya Bay reactor deal (two 944 MWe French reactors of the M310 model) was signed in 1984. Starting in 1983, China also designed its own reactor project, Qinshan-I, and construction began in 1985. Beijing planned to greatly increase China's deployment of nuclear power plants.

Meanwhile, encouraged by Western countries' enthusiasm for breeder reactor programs during that period—in particular by France's plans—China's State Council Leading Group for Science and Technology held a national expert panel discussion on the nuclear fuel cycle in 1983. This panel determined that "China's nuclear energy development must be accompanied appropriately with reprocessing" and emphasized the important roles of reprocessing in improving uranium resource utilization and reducing nuclear waste.[6] In July 1986, the State Council approved a project to build a pilot civilian reprocessing plant at the Jiuquan nuclear complex. The plant had its first test operation in 2010.

5 Xu, "Fast Reactor Development for a Sustainable Nuclear Energy Supply in China"; Gu, "The Sustainable Nuclear Energy Needs Closed Fuel Cycle."

6 Fan Zhong and Yang Xinrong, "Overcoming Difficulties to Achieve Independent Design of Pilot Plant," China Nuclear Industry, No. 6 (2006).

By 1985, however, China decided to slow its nuclear power development, because at that time nuclear power was more expensive than coal-fired power. After Daya Bay and the first reactor at Qinshan, no additional reactors were connected to the Chinese grid until 2002. By the late 1990s, however, China had returned to a modest pace of construction. China built eight additional reactors (generating a total of 6.9 GWe) from 1997 to 2002, including two domestic pressurized water reactors (PWR), two M310 PWRs from France, two VVER V-428 PWRs from Russia, and two CANDU pressurized heavy water reactors (PHWR) from Canada.

In 1995, nine years after approving construction of the pilot reprocessing plant, the State Council gave final approval to the China Experimental Fast Reactor (CEFR), China's first substantial fast-neutron reactor. The CEFR was completed in 2010. (Both the pilot reprocessing plant and the CEFR are discussed in much more detail later in this report.) No further construction of major closed fuel cycle facilities has begun since then.

Beginning in 2004, the Chinese government shifted its nuclear power development policy from "moderate development" to "active development." Anticipating a shortage of uranium supplies for China's faster nuclear power development, the China National Nuclear Corporation (CNNC) proposed plans to develop commercial reprocessing plants and breeder reactors. As the sole organization responsible for the back end of China's fuel cycle, CNNC emphasized that it wanted to be able to reprocess spent nuclear fuel from its commercial light-water reactors (LWRs), extract the plutonium, and use it to fabricate startup nuclear fuel for fast breeder reactors (FBRs).

In 2004, Professor Gu Zhongmao, an expert from the China Institute of Atomic Energy (CIAE), wrote to the national leadership regarding the urgency of developing commercial reprocessing technology, provoking a number of statements on the importance of the issue.[7] The Global Nuclear Energy Partnership (GNEP) program, launched by the U.S. Department of Energy (DOE) in 2006, further encouraged CNNC's plans for a closed fuel cycle by proposing the development of commercial reprocessing technologies amongst the select group of states that already had reprocessing technology (the nuclear-weapon states and Japan). In the GNEP concept, these states would keep the technology to themselves, but supply services to recipient states.[8]

7 Yuan Ying, "A Small Gobi Town "Devoured" International Nuclear Waste," (in Chinese), Southern Weekend, January 17, 2011, http://www.infzm.com/content/54595 (accessed January 4, 2016). For a version of this article in English, see Yuan Ying and Wang Haotong, "China's Nuclear-waste Rush," Chinadialogue, March 21, 2011, https://www.chinadialogue.net/article/show/single/en/4172-China-s-nuclear-waste-rush (accessed September 4, 2015).

8 For a description of GNEP, see the U.S. Department of Energy, "The Global Nuclear Energy Partnership: Greater Energy Security in a Cleaner, Safer World," February 6, 2006, http://energy.gov/sites/prod/files/edg/news/archives/documents/GNEP/06-GA50035b.pdf (accessed September 9, 2015). For a discussion of Chinese thinking after the announcement of GNEP, see Gu Zhongmao, Yan Shuheng, and Hao Dongqin, "Urgency for Building Chinese Commercial Reprocessing Plant," China Nuclear Industry, No. 2 (2008).

Since 2007, CNNC has been negotiating with France's AREVA for the purchase of a commercial reprocessing plant, and in 2008, CNNC and Russia's Rosatom began to discuss the prospective purchase of two fast-neutron reactors based on Russia's BN-800 design. After years of discussions, neither of these negotiations had led to a contract by late 2015. (Both of these proposals are discussed in more detail later in this report.)

In 2010, the Chinese government began charging a fee of 0.026 RMB/kWh (approximately 4.2 mill/kWh at 2014 exchange rates, or 7.1 mill/kWh if converted at purchasing power parity) from commercial PWRs that had been operating for at least five years, to finance the costs of spent fuel management.[9] The uses of the fund include: (a) spent fuel shipments (since September 2003, spent fuel has been shipped to the Jiuquan Spent Fuel Wet Storage Pool located near the pilot reprocessing plant); (b) away-from-reactor storage; (c) spent fuel reprocessing at the pilot reprocessing facility; (d) construction, operation, improvement, and decommissioning of commercial reprocessing plants; and (e) other fees for spent fuel management and disposal.[10] It is worth noting that in the United States, the equivalent charge is far less, 1 mill/kWh, and was judged likely to be sufficient to finance the costs of transport and direct disposal of spent nuclear fuel; it appears that the Chinese government has effectively acknowledged, with this charge, that reprocessing is likely to be significantly more expensive than direct disposal would be.

In November 2011, CNNC established the CNNC Ruineng Science and Technology Co., Ltd., which is responsible for siting, designing, constructing, investing in, and managing the spent fuel reprocessing and mixed-oxide fuel fabrication facilities, away-from-reactor (AFR) storage of spent fuel, and R&D on reprocessing and recycling technologies.[11]

In December 2011, the National Energy Administration (NEA) under the National Development and Reform Commission (NDRC) issued the 12th five-year energy plan, which called for completion of the spent fuel reprocessing "demonstration" project—a plant with planned capacity to process 200 metric tons of heavy metal in spent fuel per year (tHM/yr)—by 2020.[12] In 2012, CNNC issued the "Long Teng 2020 (Dragon Soars

9 One mill is 0.001 U.S. dollar, or a tenth of a cent.

10 National Development Reform Commission, Ministry of Industry and Information Technology, "Notice on the Nuclear Power Plant Spent Fuel Management Fund and Interim Measures" (in Chinese), July 12, 2010, http://www.mof.gov.cn/zhengwuxinxi/caizhengwengao/2010nianwengao/wengao6/201009/t20100903_337280.html (accessed January 4, 2016). The two CANDU PHWRs were excluded from this fee, as their fuel is not expected to be reprocessed.

11 China Nuclear Energy Association, China Nuclear Energy Yearbook 2012, (Beijing: China Atomic Energy Press, 2012).

12 Throughout this report, all references to tons refer to metric tons.
National Energy Administration, National Energy and Technology Plan during the 12th five-year period (2011–2015), March 2011, http://www.nea.gov.cn/131398352_11n.pdf (accessed January 4, 2016).

2020)" technology innovation plan that selected the 200 tHM/yr demonstration plant as one key project. The government eventually approved the demonstration plant in early 2015. In March 2015, CNNC established Longrui Co., Ltd., which is to be responsible for the 200 tHM/yr plant, leaving CNNC Ruineng Co., Ltd., responsible for the 800 tHM/yr plant.[13] In July 2015 CNNC started construction activities at the CNNC Gansu Nuclear Technology Industrial Park.[14] While the government approved the project, it is not clear if it has committed the full amount needed for construction and operation of the facility.

2.2 China's Nuclear Power Plans

China's fuel cycle policies are integrally linked to its expectations for large-scale growth of nuclear power. The Fukushima accident temporarily slowed the momentum of China's development of nuclear power. All new construction starts were put on hold while China reviewed the safety of existing reactors and considered its nuclear safety rules.

In October 2012, after comprehensive post-Fukushima safety inspections on all plants in operation and under construction, the State Council issued a new "Medium- and Long-Term Nuclear Power Development Plan (2011–2020)," which reconsidered nuclear safety and the pace of nuclear energy development.[15] The plan included: (a) a return to normal construction; (b) a "scientific" approach toward choosing new reactor sites, with a limited number of coastal facilities based on proven designs and a temporary ban on inland nuclear power projects; and (c) a requirement that all future nuclear power projects should meet the world's highest safety standards, which in essence means the safety standards for third-generation (or Gen III) reactors. Under this 2012 plan, China hoped to grow its total nuclear capacity to 40 GWe by 2015 and 58 GWe by 2020.[16] While still faster than the target of 40 GWe by 2020 set in the 2006 official plan, these targets illustrate a slower pace of development than the projected 70–80 GWe by 2020 prior to the Fukushima accident.

13 Yue Qi, "China establishes its first national nuclear technology industrial park and begins industrialization of spent fuel reprocessing in Gansu," *National Business Daily*, August 25, 2015, http://www.nbd.com.cn/articles/2015-08-25/940911.html (accessed January 4, 2016); Hui Zhang, "China is said to be building a demonstration commercial reprocessing plant," *IPFM Blog*, September 25, 2015, http://fissilematerials.org/blog/2015/09/china_is_said_to_be_build.html (accessed January 4, 2016).

14 Yue Qi, "China establishes its first national nuclear technology industrial park and begins industrialization of spent fuel reprocessing in Gansu."

15 Central People's Government of the People's Republic of China, "Wen Jiabao chairs executive meeting of the State Council," October 24, 2012, http://www.gov.cn/ldhd/2012-10/24/content_2250357.htm (accessed January 4, 2016).

16 The Information Office of the State Council, *China's Energy Policy 2012*, October 24, 2012, http://news.xinhuanet.com/english/china/2012-10/24/c_131927649.htm (accessed January 4, 2016).

In June 2014, the State Council published the "Energy Development Strategy Action Plan (2014–2020)," with the goal of transitioning China towards a "clean, efficient, safe and sustainable" energy portfolio.[17] This strategy, which plans for non-fossil resources to account for 15 percent of China's energy, focuses more on the growth of renewable resources such as wind and solar power, which respectively have targets of 200 GWe and 100 GWe by 2020,[18] than nuclear energy, which was held at 58 GWe by 2020 with 30 GWe to be under construction at that time.

In November 2014, Chinese President Xi Xingping and U.S. President Barack Obama agreed on a climate initiative, in which China pledged to achieve peak CO2 emissions by "around 2030," and to get "around 20 percent" of primary energy from non-fossil sources by 2030.[19] By Chinese government estimates, China was getting 11.2 percent of primary energy from non-fossil sources in 2014, so meeting the goal will require almost doubling this share by 2030.[20] That challenging goal may lead to additional emphasis on expanding nuclear energy.

In practice, the 2015 nuclear energy target was not achieved, as by November 2015, China had operating reactors with 29 GWe of installed capacity. Until early 2015, many argued that China was unlikely to achieve its 2020 target of 58 GWe either, because it would require building a very large number of reactors in a short time. This was a major challenge, especially since China had approved only seven units over the last four years. However, as the government approved eight new reactors (about 9 GWe) during 2015, and brought eight new power plants totaling more than 8.2 GWe on-line during the year, the target of 58 GWe now appears more achievable. Nevertheless, in the wake of the Fukushima accident, Chinese citizens are increasingly in favor of renewable energy, and it is not clear whether the central government will pursue "aggressive" development of nuclear power in the future.

Past experience suggests that the central government's commitment to commercializing reprocessing and fast-neutron reactors will be dependent on its assessment of the importance of nuclear power in China's long-term energy development strategy. Without strong direction from the central government, CNNC is unlikely to spend many billions of dollars building a large reprocessing plant or large fast-neutron reactors.[21]

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17 The State Council of the People's Republic of China, *Energy Development Strategy Action Plan (2014-2020)*, November 19, 2014, http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm (accessed January 4, 2016).

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

19 "U.S.-China Joint Announcement on Climate Change" (Washington, D.C.: The White House, November 11, 2014).

20 "Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions" (Beijing: National Reform and Development Commission, June 30, 2015).

21 Communications with CNNC nuclear experts in Beijing, November 2014.

In practice, China has very limited experience with reprocessing spent fuel from civilian nuclear power plants. As discussed in more detail below, it started operating a pilot scale reprocessing facility with a design capacity to process spent fuel containing 50 tHM/yr in December 2010, but the facility operated for only ten days. The operators have been working to resolve technical problems with the facility ever since. While the CNNC has been negotiating with AREVA over the purchase of a commercial reprocessing plant with a capacity of 800 tHM/yr, it is not clear that this deal will be supported financially by the central government.

Finally, even the advocates of a closed fuel cycle acknowledge that there is no real national plan yet for reprocessing and recycling. Many of CNNC's plans for commercial reprocessing and breeder reactors are still at the stage of recommendations, and their future is not guaranteed.[22] As we discuss below, there are good reasons for China to consider delaying investments in large reprocessing facilities and breeder reactors.

2.3 Spent Fuel Storage

One major motivation for developing commercial-scale reprocessing is to reduce the burden of spent fuel storage at reactor sites. If China meets the 2014 Energy Plan target of 58 GWe of nuclear power by 2020, it will then be discharging approximately 1100 tons of spent fuel per year.[23] Spent fuel discharges will increase significantly as China deploys more reactors.[24]

Most of this spent fuel, however, can be stored in the spent fuel pools of the reactors that

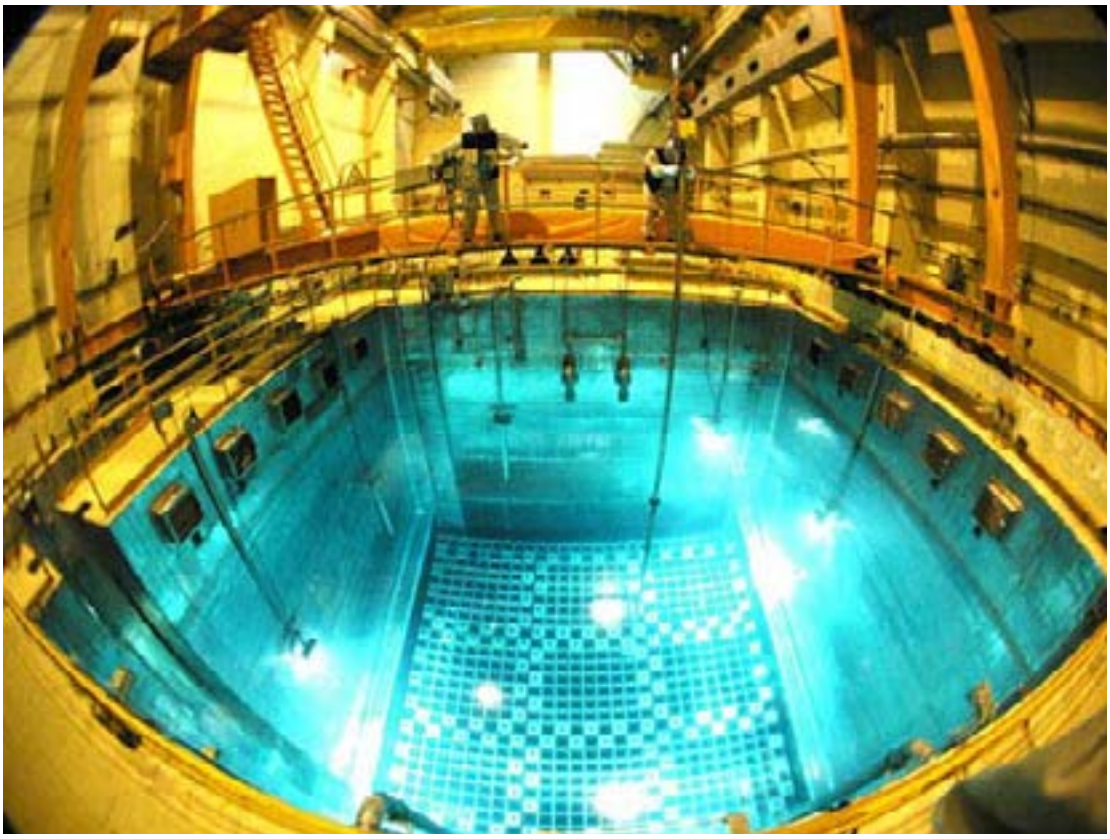
22 Gu Zhongmao, "Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China," (presentation, Workshop on Alternative East Asian Nuclear Energy Futures, Singapore, October 15–16, 2014).

23 The installed capacity will primarily be PWRs, with the exception of the two Qinshan-III CANDU PHWRs that store their spent fuel in dry casks. Only PWRs account for the total new installed capacity. From 2014 to 2020, we assume that the PWRs have an average burn-up rate of 50 GWd/t for LEU fuels at enrichment of 4.5 percent (w/o) and a capacity factor of 85 percent, thus discharging an annual mass of spent fuel of approximately 20 tons/GWe. Since 2002, China has successfully implemented higher fuel burnup in its operations at the Daya Bay reactors. For more information, see Xiao Min, Zhou Zhou, and Nie Lihong, "Nuclear fuel cycle scenarios at CGNPC," (presentation, "Atalante 2008: Nuclear fuel cycle for a sustainable future," Montpellier, France, May 19–23, 2008, http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/40/034/40034673.pdf (accessed January 4, 2016)).

24 Just prior to the Fukushima accident, an authoritative 2011 study proposed that China should install 200 GWe of nuclear power (about 10 percent of its total electricity generation) by 2030 and 400-500 GWe (approximately 15 percent of its total electricity generation) by 2050. See the China Academy of Engineering, *China's Medium- and Long-Term Energy Development Strategy (2030, 2050)* (Beijing: Science Press, 2011). After the Fukushima accident, CNNC experts have made similar projections. For more information, see Gu,"Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China" and Zhang Donghui, "Fast Reactor Development Strategy In China" (presentation, International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios, Paris, France, March 4–7, 2013).

discharged it (see Table 2.1). Only the two PWRs at the Daya Bay NPP have reached their full storage capacity for spent fuel, more than a decade ago. Since then, Daya Bay has been shipping spent fuel to the interim storage pool at the pilot reprocessing plant (Figure 2.1). The 500-ton capacity of that pool was filled in 2014, but a second 760-ton pool at the pilot reprocessing plant has been completed and is waiting for National Nuclear Safety Administration (NNSA) approval for operation (see Box 2.1).[25]

Figure 2.1: **Spent Fuel Pool at Pilot Reprocessing Plant**



Source: Zhang Donghui, "Status of China National SFR Program" (presentation, International Workshop on Prevention and Mitigation of Severe Accidents in Sodium-Cooled Fast Reactors, Tsuruga, Japan, June 12–13, 2012)

Based on the installed capacity of operating reactors, reactors under construction, and the projection of 58 GWe by 2020, the authors of this report estimate that China will not need additional spent fuel storage until approximately 2027 with the 760-ton pool at the pilot reprocessing plant. If an additional 3000-ton storage facility is built before 2027, China will not need additional spent fuel storage until 2035.[26] Moreover, the pilot reprocessing

25 Communication with a National Nuclear Safety Administration expert, January 2015.

26 This assumes that the annual discharged mass of spent fuel from 2014 to 2020 is approximately 20 tons/GWe for the PWRs. The 500-ton pool at the pilot plant reached full capacity in 2014. The new plants have a 20-year storage capacity. This also assumes no spent fuel is moved from pools to dry casks for storage.

plant is located in the very remote Gobi desert, a less populated area, and has plenty of space for simple modular expansion. Thus, China will have little pressure to reduce the burden of spent fuel storage in the next two decades.

China could take measures to delay the requirement for additional storage, including building larger pools for new reactors and on-site dry cask storage. At PWR sites, China does not use dry cask storage yet. However, the China General Nuclear Power Corporation (CGN, formerly known as the China Guangdong Nuclear Power Corporation) has been seeking to develop on-site, interim, dry-storage for its PWRs, as illustrated by its cooperation with China's NNSA on ensuring the safety of dry-storage and its discussion with U.S. firms on purchasing dry casks.[27] In 2014, a CGN official emphasized that a demonstration program of dry storage would be one focus in the coming three-year plan of science and technology renovation.[28] Given that CNNC is responsible for off-site spent fuel storage and reprocessing, CGN, as a competitor, may want to save more money to develop its on-site dry storage. Dry cask storage would allow for decades of safe, secure, and cost-effective storage, while leaving both reprocessing and direct disposal options open for the future.[29]

China has time to take a "wait and see" approach on its commercial reprocessing plans. Constrained by its national reprocessing policy, China's nuclear industry did not build larger away-from-reactor pools or on-site dry storage during the past several decades. While spent fuel continues to build up and the future of commercial reprocessing remains unclear, the government should adopt a flexible approach toward spent fuel management. Developing spent fuel management technology and infrastructure will require more attention, financial support, and a management plan to ensure the long-term safety and sustainability of a large-scale nuclear power program.

Box 2.1: **Development of Spent Fuel Storage in China**

At operational Chinese nuclear power plants built before 2005, the on-site spent fuel pools

27 Communication with National Nuclear Safety Administration expert, January 2015.

28 Xinhua News, "What are the prospects for technological innovation for CGN over the next three years?" (in Chinese) October 31, 2014, http://news.xinhuanet.com/energy/2014-10/31/c_127163425.htm (accessed January 4, 2016).

29 For more analysis of interim storage options, see Matthew Bunn, John P. Holdren, Allison Macfarlane, Susan E. Pickett, Atsuyuki Suzuki, Tatsujiro Suzuki and Jennifer Weeks. *Interim Storage of Spent Nuclear Fuel—A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management* (Cambridge, Mass.: Managing the Atom Project, Harvard University and Project on Sociotechnics of Nuclear Energy, University of Tokyo, June 2001).

were designed to accommodate ten years of spent fuel discharges. Under the closed nuclear fuel cycle policy, spent fuel would be removed to a reprocessing site after five years. Newer plants are usually built with 20 years of storage capacity, mainly through pool dense-racking technology. Currently, all spent nuclear fuel at NPPs, except the spent fuel from the Daya Bay NPP, is stored on-site in the plants' spent fuel pools. The pools at the Daya Bay NPP, whose two pressurized water reactors came online in 1993 and 1994, reached full capacity around 2003. Since then, China has transported spent fuel semiannually from the Daya Bay nuclear power plant (which discharges about 50 tons of spent fuel each year) to the Centralized Wet Storage Facility (CWSF) at the pilot reprocessing plant. A total of approximately 500 tons of spent fuel was shipped by the end of 2014.

The construction of the first stage of CWSF started in May 1994. The pool has a storage capacity of 500 tons for spent fuel from PWRs and 50 tons for fuel from research reactors.[A] The pool began to receive spent fuel from the Daya Bay NPP in 2003 and reached full capacity by 2014. Meanwhile, in 2013 and 2014, China transferred some spent fuel from the pools at the Daya Bay reactors to the nearby pools at the Ling Ao NPP. CNNC has built another 760-ton pool at the pilot reprocessing plant (consisting of two 380-ton pools), and is waiting for NNSA approval for operation. Proposals are also being considered to include a 3000-ton storage pool in a larger reprocessing plant, if one is built.[B]

In 2008, CNNC began construction of an on-site, interim, dry-storage facility for its two CANDU reactors at Qinshan-III, since China has no plans to reprocess any spent fuel from heavy water reactors. The two CANDU reactors, with lower burn-up, discharge 176 tons of spent fuel annually.[C] There are plans to construct 18 MACSTOR-400 concrete storage modules at a rate of two modules every five years, which could expand the on-site spent fuel storage capacity to 40 years.[D]

A National Nuclear Safety Administration, Annual Report 2006 (in Chinese).

B National Nuclear Safety Administration, Annual Report 2006 (in Chinese). Deng Guoqing, "Overview of Spent Fuel Management in China" (presentation, IAEA International Conference on Management of Spent Fuel from Nuclear Power Reactors, Vienna, Austria, June 3, 2010).

C Jiang Yunqing, "China's Spent Fuel Treatment: The Present Status and Prospects," Status and Trends in Spent Fuel Reprocessing, Proceedings of an Advisory Group Meeting (Vienna: IAEA, August 1999), http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/047/30047646.pdf (accessed January 4, 2016).

D L.M. Zheng and C. Shen, "Status and technology of interim spent fuel dry storage facility for PHWR nuclear power plants," Nuclear Safety 1, No. 1 (2005): 39–44.

Table 2.1 shows the spent fuel storage status at each operating Chinese nuclear reactor. It seems clear that China will need more storage than the wet pools currently planned will provide. China could provide whatever storage is needed by using storage in dry casks, either at reactor sites or at centralized locations. Figure 2.2 shows the additional spent fuel storage China will need from 2015–2040. The 500-ton pool at the pilot plant was full in 2014. The table assumes that a PWR does not require additional spent fuel storage until its pool is full.

Figure 2.2: **Cumulative Additional Storage Demands Beyond Storage in Reactor Pools from 2015 to 2040**

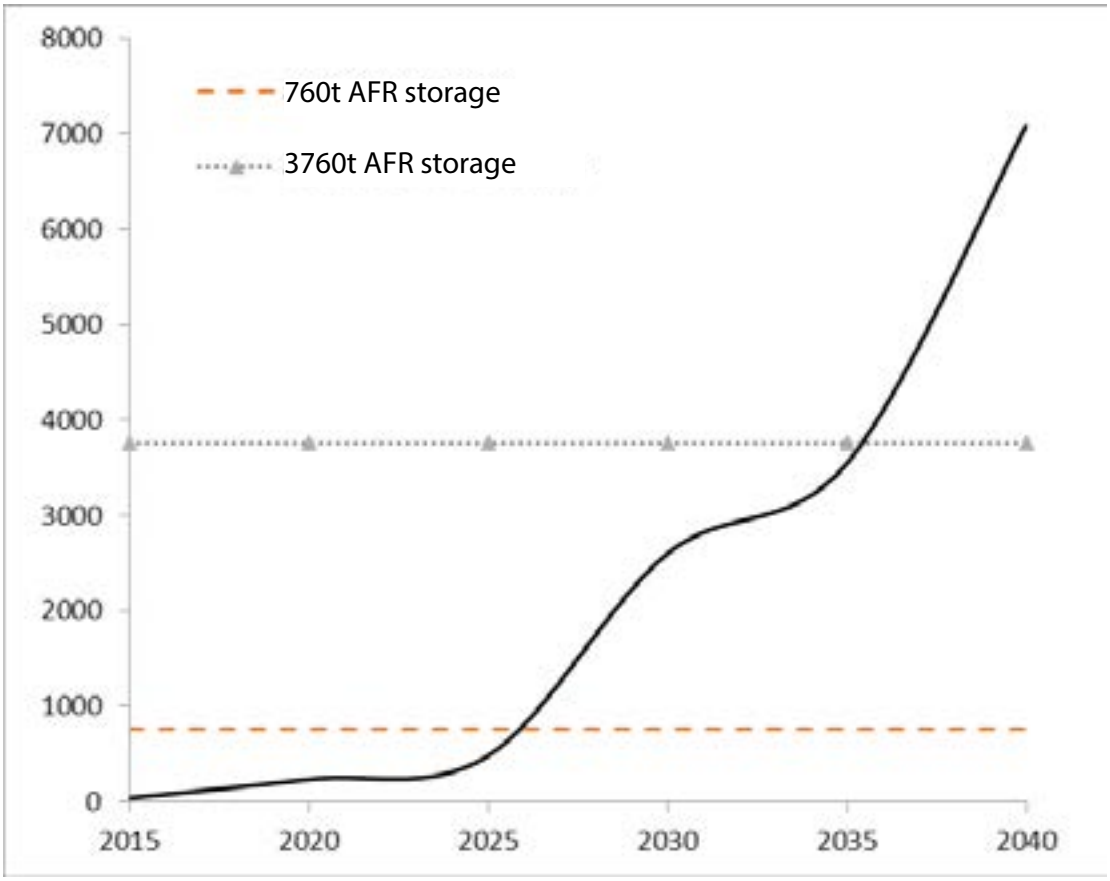


Table 2.1: **Current Status of Spent Fuel Storage at NPPs in China** (as of end of 2014)

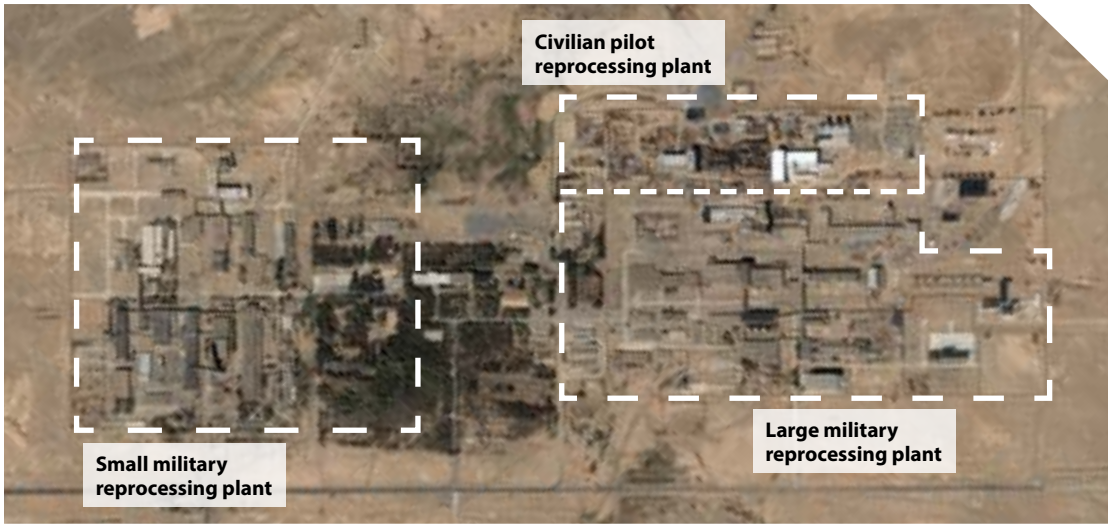
Reactor	Gross Power (MWe)	First Grid Connection	Spent Fuel Storage Method	On-site Spent Fuel Storage Capacity	Storage Expected to Reach Capacity
Qinshan I-1	310	12/1991	Dense-pack/Pool size expansion	35 years	2026
Daya Bay 1	984	08/1993	Wet storage	10 years	2003
Daya Bay 2	984	02/1994	Wet storage	10 years	2004
Qinshan II-1	650	02/2002	Dense-pack/ Wet storage	20 years	2022
Qinshan II-2	650	03/2004	Dense-pack/ Wet storage	20 years	2024
Lingao1	990	02/2002	Dense-pack/ Wet storage	20 years	2022
Lingao2	990	09/2002	Dense-pack/ Wet storage	20 years	2022
Qinshan III-1	728	11/2002	On-site wet/dry storage	40 years	2042
Qinshan III-2	728	06/2003	On-site wet/dry storage	40 years	2043
Tianwan 1	1,060	05/2006	Wet storage	20 years	2026
Tianwan 2	1,060	05/2007	Wet storage	20 years	2027
Qinshan II-3	660	08/2010	Wet storage	20 years	2030
Lingao 3	1,080	09/2010	Wet storage	20 years	2030
Lingao 4	1,080	08/2011	Wet storage	20 years	2031
Qinshan II-4	660	04/2012	Wet storage	20 years	2032
Ningde I-1	1,080	04/2013	Wet storage	20 years	2033
Ningde I-2	1,080	05/2014	Wet storage	20 years	2034
Hongyanhe I-1	1,119	06/2013	Wet storage	20 years	2033
Hongyanhe I-2	1,119	05/2014	Wet storage	20 years	2034
Yangjiang 1	1,086	03/2014	Wet storage	20 years	2034
Fuqing 1	1,080	08/2014	Wet storage	20 years	2034
Fangjiashan 1	1,080	11/2014	Wet storage	20 years	2034

Source: Yun Zhou, "China's Spent Nuclear Fuel Management: Current Practices and Future Strategies," *Energy Policy*, 39, 25 April 2011, 4360–4369. Also we assume new reactors are designed with 20 years storage capacity.

2.4 *China's Civilian Reprocessing Pilot Plant*

As noted earlier, in July 1986, the State Council approved the construction of a pilot civilian reprocessing plant at the Jiuquan nuclear complex, known as Plant 404 (See Figure 2.3). The Beijing Institute of Nuclear Engineering (BINE), CIAE, and the staff of the Plant 404 military reprocessing plant carried out the research and development of the technology for the plant. All these organizations are under CNNC. This pilot plant serves as an experimental base and personnel training center, and may become the template for designing a larger reprocessing plant in the future.

Figure 2.3: **Overview of the Jiuquan Nuclear Complex (Plant 404)**



Satellite image from August 31, 2007. The intermediate pilot reprocessing plant was the first plant for processing weapons plutonium, followed by the larger facility labeled the military reprocessing plant. The civilian pilot plant is immediately adjacent to the military reprocessing plant. Credit: DigitalGlobe and Google Earth.

The design of the civilian pilot plant was based primarily on experience derived from PUREX test facilities developed in the 1960s for the nuclear weapon program (see Box 2.2). This civilian pilot plant includes a main reprocessing facility with an estimated capacity to process 50 tons of fuel/year.[30] The plant also includes the CWSF and a hot cell laboratory with a capacity of 0.9 kg of HEU spent fuel/day, for spent fuel discharged from research reactors.[31] In July 1993, the technical design of the plant was approved**.** Started in 1998 and completed in 2005, the construction of the pilot plant was fraught with

30 Gu Zhongmao, "Securing Nuclear Fuel Cycle When Embracing Global Nuclear Renaissance," (presentation, International Ministerial Conference on Nuclear Energy in the 21st Century, Beijing, China, April 20–22, 2009); Zhang, "Status of China National SFR Program."

31 Jiang, "China's Spent Fuel Treatment: The Present Status and Prospects."

difficulties, including adjusting the budget estimates twice and delays in construction.[32] Around 2000, a jingle about the project became popular: "the construction duration dragged over again, the budget estimates increased again, the quality issues appeared again."[33] After 2000, when construction was completed, it took another ten years to "debug" the facility. Finally, on December 21, 2010, it successfully conducted a hot test and CNNC pronounced it a fully operational pilot reprocessing plant. It took about 24 years from the project approval in July 1986 to the hot test in December 2010. It did not use advanced technologies for key equipment, including fuel shearing and dissolution, automatic controls and remote-repair techniques in a radioactive environment, and plutonium processing.[34]

Figure 2.4: **The Pilot Civilian Reprocessing Plant at the Jiuquan Nuclear Complex**



Photo source: Gu, "Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China."

32 Gao Lei, "The Pilot Plant: Overcoming Difficulties in the Journey on Spent Fuel Reprocessing," *China's Nuclear Industry* (in Chinese), No.7 (2007): pp.36–37.

33 "The pilot project—the cradle of China's reprocessing techniques: Interview with Director Li Guanchang of CNNC Nuclear Fuel Department," *China's Nuclear Industry* (in Chinese), No.6 (2006): pp.36–37.

34 Gu, et al., , "Urgency for building Chinese commercial reprocessing plant."

During the 2010 hot test, reprocessing operations stopped after only ten days and separation of 25.4 kg of plutonium.[35] In December 2010, many problems, including safety and security issues, were encountered or identified. These included both a large amount of waste produced and a high percentage of material unaccounted for (MUF).[36] Further research and design changes are in progress.[37] Reprocessing operations have not resumed as of late 2015. CNNC plans to resume operations in 2016.

After the pilot plant conducted its hot test in December 2010, CNNC announced that, once the pilot plant reprocessed a total of 50 tHM in coming years, the plant would be expanded to a capacity of 80-100 tHM/yr. Originally, the statement projected this would occur by the end of 2015.[38] Since the plant has not come close to the original goal of reprocessing 50 tHM of spent fuel, it does not appear that CNNC has yet undertaken any expansion efforts. In 2014, a CIAE expert stated that it would take around three more years to fulfill the task of reprocessing 50 tHM of spent fuel.[39] These new projections indicate that the current effective capacity of the pilot plant may be much lower than 50 tHM/yr. Further, some nuclear experts argue that CNNC's interest in buying a commercial reprocessing plant from AREVA shows that CNNC has limited confidence in its ability to build its own larger plant economically based on the experience from its pilot plant.[40]

35 After commencing operations at the pilot reprocessing plant on December 21, 2010, China declared on December 31 in its annual INFCIRC/549 report of civilian plutonium holdings a stock of 13.8 kg of separated plutonium "in product stores at reprocessing plants." In August 2014, China reported that, as of December 2013, its total civilian stock of separated plutonium still was 13.8 kg, indicating that no additional plutonium had been separated during 2011–2013. See IAEA, "Communication received from China Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.7/10, (Vienna: IAEA, July 8, 2011), and INFCIRC/549/Add.7/13, (Vienna: IAEA, August 15, 2014). But in China's 2015 declaration, this figure was updated to 25.4 kilograms of plutonium. Chinese experts report that no additional spent fuel has been sheared, but that some additional plutonium has been separated from solutions dating from the 2010 operations. For the new figure, see IAEA, "Communication received from China Concerning Its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.7/14, (Vienna: IAEA, August 28, 2015), https://www.iaea.org/sites/default/files/infcirc549a7-14.pdf (accessed January 4, 2016).

36 Communications with Chinese nuclear experts on nuclear safety and security, Spring 2013.

37 Personal communication with personnel from CNNC, Summer 2014.

38 He Zuoxiu, "Will China become the eighth nation to have fast reactor technology?" Sciencenet, January 4, 2011, http://blog.sciencenet.cn/blog-43021-435201.html (accessed January 4, 2016).

39 Gu, "Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China."

40 He, "Will China become the eighth nation to have fast reactor technology?"

Figure 2.5: **Inside of the Pilot Plant**



Source: Zhang, "Status of China National SFR Program."

Table 2.2: **Milestones in the Development of the Pilot Reprocessing Plant**

July 1986	Project approved by the State Council
1991	Preliminary design approved by a technical review
1992	Pilot plant engineering command office established at plant 404
June 1993	Design (with improvements) formally approved by the government
1998	Construction begins
September 2003	Spent fuel pool at the site began to receive spent fuel from Daya Bay
October 2004	Tests with water conducted
December 2005	Construction completed, successful tests with acid
December 2010	Ten days of testing with nuclear material, separating 13.8 kg of plutonium; CNNC announces the plant successfully commissioned
2011-present (late 2015)	Plant not operating

Sources: "The pilot project—the cradle of China's reprocessing techniques: Interview with Director Li Guanchang of CNNC Nuclear Fuel Department," China Nuclear Industry; Lei, " The pilot plant: Overcoming difficulties in the journey on spent fuel reprocessing."

Box 2.2: **The History of China's Military Reprocessing Program**

In 1956, as soon as it launched its nuclear weapon program, China began exploring possibilities for military reprocessing. In 1962, Beijing decided first to build an intermediate-scale pilot plant (also referred to as the Small Plant, or the first project) and then build a large military reprocessing plant later (also referred to as the Large Plant, or the second project). China built both projects at the Jiuquan nuclear complex (Plant 404).

At first, China used reprocessing technologies provided by the Soviet Union. In 1964, after the Soviet Union withdrew its experts from China, China decided to switch to the PUREX method developed in the United States and published in the open literature. The intermediate pilot reprocessing plant started construction in 1965 and began operation in September 1968. The plant had a design capacity of 0.4 tons of spent fuel per day and was designed to operate 250 days a year. The pilot plant stopped plutonium separation when the larger plant began operating in 1970. The large plant stopped plutonium separation in the late 1980s. In 1969, Beijing decided to build a second military plutonium reprocessing plant (Plant 821) at Guangyuan, Sichuan province. That plant started operation in 1976 and closed around the end of 1980s.[A]

China's military reprocessing program helped lay a foundation for China's civilian back-end fuel cycle program and the 404 plant was selected as the site for the civilian pilot plant.

A Hui Zhang, "China's HEU and Plutonium Production and Stocks," *Science & Global Security*, Vol. 19, No. 1 (2011): 68–89, http://belfercenter.ksg.harvard.edu/files/huizhangSGS2011.pdf (accessed January 4, 2016).

In addition to the pilot reprocessing plant, China built a pilot plutonium-uranium mixed oxide (MOX) fuel fabrication facility nearby, with the capacity to fabricate half a ton of MOX per year. This pilot MOX plant is intended to supply fuel for China's Experimental Fast Reactor (CEFR). The CEFR, which reached criticality in July 2010, had not used any MOX fuel as of late 2015. It started up with HEU instead, with an initial core of about 240 kg of uranium enriched to 64.4 percent U-235, provided by Russia. CIAE expected to load the CEFR with MOX fuel before 2020. China has approved several research projects on the pellets, clad, rods, and subassemblies for this fuel, and plans to load test rods of MOX into CEFR for irradiation before 2017.[41]

Figure 2.6: **The Pilot MOX Fuel Fabrication Facility (0.5 tons/year) at Plant 404**



Source: Zhang, "Status of China National SFR Program."

41 Zhang, "Status of China National SFR Program."

2.5 *Proposals for an 800 tHM/yr Commercial Reprocessing Plant*

Since China revived its nuclear power development in 2004, the CNNC has urged the central government of China to fund the construction of a commercial-scale reprocessing plant.[42] In November 2007, CNNC signed an agreement with France's AREVA to undertake feasibility studies on building a reprocessing plant with a capacity of 800 tons of spent fuel per year, with integrated MOX fabrication. Following this, CNNC and AREVA signed an industrial agreement on cooperation in spent fuel treatment and recycling in November 2010.[43] That same year, CNNC preselected Jinta county of Gansu province (northeast of Yumen city, where Plant 404 is located) as the site for the proposed reprocessing plant and set up the CNNC Gansu Spent Fuel Reprocessing Project Office in the nearby city, Jiayuguan.[44] The population density within 20 km around the site is very low and there are no industrial, agricultural, or health facilities within 15 km of the site. As of 2009–2010, CNNC expected this larger plant to be operational by 2025.[45] As of 2015, however, it appears that the Gansu site will be the 200 tHM/yr plant, not the 800 tHM/yr plant.

It appears likely that the 800 tHM/yr plant, if it is built, would would be sited in the east coastal area. In July 2015, CNNC Ruineng started working on a preliminary evaluation of the seismic safety at two pre-selected coastal sites for the proposed 800 tHM/yr plant, also intended to have a spent fuel storage capacity of 6000 tons. The evaluation work was planned to be finished by September 30, 2015.[46]

Two key issues, however, have delayed the French-Chinese negotiations: price and technology transfer. CNNC nuclear experts considered AREVA's asking price of €20–€25 billion (around $25–$31 billion in 2014 dollars) to be too high. In response, CNNC reportedly offered €8 billion and then later increased their offer to €10 billion. AREVA

42 Gu Zhongmao, Yan Shuheng, and Hao Dongqin, "Urgency for building Chinese commercial reprocessing plant," China Nuclear Industry, No. 2 (2008).

43 Gu, "Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China."

44 Both Yumen city and Jinta county belong to the Jiuquan area. Also see Yuan, "A small Gobi town "devoured" international nuclear waste."

45 See Dai Yunxiu, "Introduction of the large scale reprocessing plant in China," (presentation, International Conference on Management of Spent Fuel from Nuclear Power Reactors, Vienna, Austria, June 3, 2010); Gu Zhongmao, "Securing nuclear fuel cycle while embracing global nuclear renaissance," (presentation, International ministerial conference on nuclear energy in the 21st century, Beijing, China, April 20-22, 2009)

46 "Sino-French nuclear negotiations moves forward and evaluation of the seismic safety at coastal sites starts," (Chinese) August 25, 2015, http://www.bjztb.gov.cn/news/201508/t9420808.htm (accessed January 4, 2016).

rejected both offers.[47] Further, there were political differences of opinion, including France's requirement that China accept IAEA safeguards in the plant and China's interest in transferring the entirety of AREVA's technology.

In April 2013, CNNC and AREVA signed a letter of intent that covers project details about construction, performance, and responsibilities.[48] The 2013 accord was followed by another agreement in March 2014 to continue planning the project and complete a business case for it.[49] Most recently, CNNC and AREVA signed a memorandum of understanding (MoU) in June 2015 formally indicating the conclusion of technical discussions and the start of negotiations on business aspects.[50]

In short, China and France have signed accords on this plant in 2007, 2010, 2013, 2014, and 2015, without yet having reached agreement on the key issue of price. Experts have emphasized that price is the key for such commercial contracts and that until the price is settled the deal is far from complete.[51] Similarly, CNNC has been negotiating with Russia on purchasing BN-800 breeder reactors since 2008, but has not signed a final deal yet due to disagreements over the price.

Moreover, given that the design and construction of commercial reprocessing plants involve very complicated and technical systems engineering, CIAE experts suggest that it would take at least 15 years to progress from a completed design to an operational plant.[52] Even if the plant starts construction in 2015, it is optimistic to project that it will be commissioned in 2030.

There is still disagreement among Chinese nuclear experts regarding whether to import a commercial reprocessing plant. Some analysts argue that obtaining foreign commercial reprocessing technology is a fast track solution to improving China's reprocessing capabilities. Others believe that China should use its indigenous technology to maintain greater independence.[53]

47 "China: Is France to Blame for CNNC's Back-End Problems?" *Uranium Intelligence Weekly*, December 19, 2011.

48 AREVA signs a series of strategic agreements with its Chinese partners, April 25, 2013, http://www.areva.com/scripts/news/publigen/content/templates/Show.asp?P=9812&L=EN (accessed January 4, 2016).

49 AREVA signs a series of agreements with its Chinese partner CNNC, March 26, 2014, http://www.areva.com/scripts/news/publigen/content/templates/Show.asp?P=10169&L=EN (accessed January 4, 2016).

50 France-China: AREVA Signs Three Agreements with its partners CNNC, CGN and EDF, June 30, 2015, http://www.areva.com/scripts/news/publigen/content/templates/Show.asp?P=10556&L=EN (accessed January 4, 2016).

51 Communications with CNNC nuclear experts, November 2014.

52 Gu Zhongmao, Yan Shuheng, and Hao Dongqin, "Urgency for building Chinese commercial reprocessing plant."

53 He, "Will China become the eighth nation to have fast reactor technology?"

2.6 *Proposals for a 200 tHM/yr Demonstration Reprocessing Plant and MOX Fuel Fabrication Plant*

While it was still negotiating with AREVA on buying a French-designed plant, CNNC began to plan a medium-scale demonstration plant after the pilot reprocessing plant finished its hot test in December 2010. This demonstration plant would be a scale-up of the pilot plant, with a capacity of 200 tHM/yr.[54] Unlike the 800 tHM/yr plant slated for China's eastern coast, the planned site for the smaller plant is the Jinta region of Gansu, and CNNC Longrui Co. Ltd. would be responsible. Siting these new facilities away from Plant 404 may suggest that CNNC Ruineng does not wish to share the revenue from operating the new facilities with Plant 404. In addition, collocating new plants—in particular, one purchased from AREVA—at Plant 404, which hosts former military reprocessing plants, could introduce vulnerabilities for China, such as outsiders collecting dust particles that could reveal classified aspects of China's weapons plutonium.

Additionally, by 2020 CNNC plans to build a small MOX fuel fabrication plant with a capacity of 20 tons/year (and plutonium content greater than 16 percent) at Jinta, adjacent to the 200 tHM/yr reprocessing plant. In October 2010, GDF Suez Belgian subsidiary Tractabel, with Belgonucleaire and the nuclear research center SCK-CEN, signed a framework agreement with CNNC for the construction of a pilot MOX fuel fabrication plant in China, but the deal reportedly fell through.[55]

2.7 *China's Experimental Fast Reactor*

In parallel with development of the pilot reprocessing plant, CIAE (under CNNC) has developed the CEFR. With a design similar to Russia's BOR-60 experimental fast reactor (built as part of the effort to develop the BN-600), it is a sodium-cooled, experimental fast reactor with a power capacity of 25 MWe (65MWt). It is located about 40 km away from the city of Beijing. The Ministry of Science and Technology (MOST) listed the FBR program as part of the national high-technology R&D "863 Program" in 1986. The conceptual

54 See He, "Will China become the eighth nation to have fast reactor technology?"; Zhao Zhixiang, "Closed Nuclear Fuel Cycle and Sustainable development of nuclear power in China," (presentation, Harvard –Peking Workshop on Nuclear Reprocessing, October 15, 2011); Zhang, "Status of China National SFR Program (Presentation, International Workshop on Prevention and Mitigation of Severe Accidents in Sodium-cooled fast Reactors, Tsuruga, Japan, June 12–13, 2012).

55 "China: Progress on FBR/HTGRs, But Obstacles Remain," *Uranium Intelligence Weekly*, August 8, 2011.

design of the CEFR was completed between 1990–1992 and the project was approved in 1995. In May 2000, China began construction on the CEFR.[56] The CEFR went critical in July 2010, ten years after the start of construction, and had 40 percent of its full power incorporated to the grid by July 2011. However, the reactor was online for only 26 hours during 2011—producing the equivalent of one full-power hour—and then was not connected again during 2012 and 2013.[57] Three years after its last test, the CEFR successfully completed a test operating at full capacity for 72 hours on December 15–18, 2014.[58] It took about 19 years from the project approval in 1995 to achieving operation at full capacity in 2014. The CEFR continues to operate intermittently at somewhat lower power levels, for R&D purposes.

Figure 2.7: **China's Experimental Fast Reactor**



The CEFR is located in the Fangshan District on the outskirts of Beijing. Its first grid connection was on July 21, 2011.
Source: http://news.xinhuanet.com/english2010/china/2011-07/21/c_131000739.htm

56 See, Xu, "Fast Reactor Development for a Sustainable Nuclear Energy Supply in China."

57 International Atomic Energy Agency, "China Experimental Fast Reactor," *Power Reactor Information System*, http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=1047, accessed September 10, 2015).

58 Xinhua News, "China experimental fast reactor runs at full capacity," December 19, 2014, http://www.cs.com.cn/english/ei/201412/t20141219_4595461.html (accessed January 4, 2016).

As with the pilot reprocessing plant, the CEFR met a multitude of difficulties during the construction including: changes to the technical configuration, key systems, and the function of major components; difficulties with the installation of the integrated reactor block, especially the internals and the reactor vessel; and a lack of engineering management experience on the integrated design of a pool-type fast reactor. Thus, the project experienced a long construction time. The total capital cost estimate of CEFR was adjusted two times, with each new figure almost doubling the previous one.[59]

59 Yang Hongyi, "Economic Issues of Fast Reactor in China" (presentation, Technical Meeting on Fast Reactors and Related Fuel Cycle Facilities with Improved Economic Characteristics, Vienna, Austria, September 11–13, 2013, https://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-09-11-09-13-TM-NPTD/7.yang.pdf (accessed January 4, 2016)).

Table 2.3: **Development of CEFR**

1990–1992	Conceptual design
1993	Consultation with Russian FBR Association and optimization
December 29, 1995	Project approved
November 7, 1997	Preliminary design approved
1997–2004	Ordering components
October 1998	Beginning of site preparations
May 1998–May 2000	Preliminary safety analysis report review
May 30, 2000	Construction started
August 15, 2002	Close of the reactor building
2004–2007	Installation of equipment
December 25, 2008	Completion of reactor block installation
September 2009	Fuel loading license issued
June 2010	Fuel loading license re-issued after reviewing public letter on safety
July 21, 2010	First criticality
July 2011	Connected to the grid at 40 percent power
December 15–18, 2014	Operation at 100 percent rated power for 72 hours
December 2014	CNNC announced it had fully mastered the core technologies in fast reactor design

Source: Xu, "Fast Reactor Development for a Sustainable Nuclear Energy Supply in China"; Yang, "Economic Issues of Fast Reactor in China"; Zhang, "Status of China National SFR Program."

2.8 *Proposals for Fast Breeder Reactors in China*

After China adopted "active" development of nuclear power around 2004, CNNC promoted the development of fast reactors in China. Initially, China's fast neutron reactor experts proposed a three-stage development process starting with the 20-MWe CEFR project (see Table 2.4). However, the proposed plans have been scaled back and delayed since 2013. In 2010, CIAE experts proposed deploying several demonstration fast reactors at Sanming in Fujian province, including two 800 MWe BN-800 FBRs from Russia by 2018 and one indigenous 1000 MWe China Demonstration Fast Breeder Reactor (CDFBR) by 2028. However, by 2013, they decided to focus on deploying one indigenous 600 MWe CFR-600 reactor by 2023.[60]

CNNC and Rosatom (Russia's state nuclear power corporation) began cooperating in 2008 on the Sanming fast reactor project, and, in October 2009, CNNC signed a high-level agreement with Rosatom to collaborate on the development of the two BN-800 FBRs. Construction of the first reactor was originally planned to start in August 2011.[61] Once 2011 arrived, CIAE experts expected the start of construction on these reactors to be in 2013 and 2014, respectively.[62] However, there have been long delays in the negotiation. Chinese experts argue that Russia's price is too high. In 2011, Sanming Nuclear Power Corporation, the group in charge of the project, reportedly made an offer of approximately $3.1 billion per unit— 60 percent more expensive per kilowatt of capacity than an AP-1000 reactor in China (based on an estimate of $1,940 per kilowatt, or $2.425 billion, by the president of China's AP-1000 developer, the State Nuclear Power Technology Corporation [SNPTC]), though it is not clear that exactly the same elements of cost are included in these two reported figures.[63] Moreover, CNNC seeks the intellectual property rights to the technology, which Rosatom is reluctant to provide.[64] Meanwhile, strong voices within China favor China developing its own fast neutron technology rather than importing it. Nonetheless, China's government has not officially either approved or rejected the plan for Russian FBRs. Currently, it is not clear when, or indeed if, the project will go forward.

60 Yang, "Economic Issues of Fast Reactor in China."

61 "Nuclear Power / BN-800 build in China may be formalized this summer," June 6, 2012, Nuclear.Ru.

62 Communication with a Chinese FBR expert in Beijing, March 2011 .

63 "China: Progress on FBR/HTGRs, But Obstacles Remain."

64 Personal communication with a CIAE expert, December 2013.

While the negotiation on the BN-800 purchase was idling, CIAE decided in 2013 to focus on developing an indigenous 600 MWe CFR-600. It planned to finish the concept design by February 2014 and the primary process design by December 2015.[65] Following this, CIAE planned to start construction on the CFR-600 in 2017 and begin operation in 2023. This would still require a government decision to finance construction of the plant, however. The 200 tHM/yr reprocessing plant and the 20 tons/year MOX fuel fabrication plant would provide operational support for the CFR-600.

Since 2013, CIAE experts have also proposed developing the first commercial fast reactor—a 1000 MWe CFR-1000 based on the experience to be gained from the CFR-600. However, as one CIAE expert and advocate of China's closed fuel cycle stated recently, "China needs at least another 20-30 years' efforts before the commercialization of a fast reactor energy system, and there are so many uncertainties ahead. It is beyond our ability to draw a clear picture for 20 years further."[66]

In practice, even the head of the fast reactor division of CIAE states that the deployment of commercial fast reactors in China will depend on several factors. Among these factors are the cost of uranium; safety validation and the feasibility of an inland site; and the cost of electricity from an FBR compared to that of a coal power plant.[67]

Before commercializing fast-neutron reactors, China would need to construct a commercial scale breeder fuel fabrication plant along with a reprocessing plant for breeder reactor fuel.

65 It was reported in March 2014 that the concept design had been completed and the primary process design was ongoing. See Wan Gang, "An authoritive interpretation on China's FBR development," March 14, 2014, http://www.ns.org.cn/c/cn/news/2014-03/14/news_1138.html (accessed January 4, 2016).

66 Gu, "Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China."

67 Zhang, "Fast Reactor Development Strategy In China."

Table 2.4: **CIAE's Proposed China FBR Development Strategy**

Development Strategy		Reactor type	Power (MWe)	Commissioning
Experimental Stage		CEFR	20	2010
Demonstration Stage	Pre-2013 Plans	CDFR (e.g. BN-800) CDFBR	600~900 1000~1500	2018~2020 2028
	Post-2013 Plans	CFR-600* BN-800?	600 800	2023 ?
Commercialization Stage	Pre-2013 Plans	CCFR CCFBR	800~900 1000~1500	2030 2030~2031
	Post-2013 Plans	CFR-1000	1000	2034-2044?

Source: Xu, "Fast reactor development for a sustainable nuclear energy supply in China"; Gu, "Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China"; Zhang, "Fast Reactor Development Strategy In China"; Yang, "Economic Issues of Fast Reactor in China."

**Confirmed plan by CIAE*

CDFR: China demonstration fast reactor
CCFR: China commercial fast reactor
CDFBR: China demonstration fast breeder reactor
CCFBR: China commercial fast breeder reactor
CFR: China fast reactor, a new name after 2013.

3. The Cost of Reprocessing: China's Experience & Projections

China's current approach to estimating the likely future cost of commercial-scale reprocessing plants in China is to extrapolate from China's experience with its pilot-scale reprocessing plant. This chapter will describe that experience and the extrapolations Chinese experts have made based on it. The next chapter will explore international experience with the cost of commercial reprocessing facilities, and what China might learn from that experience.

3.1 The Cost of China's Pilot Reprocessing Plant

The pilot plant's construction costs included three major parts: reprocessing facilities (including waste management), spent fuel storage, and transportation.[68]

The initial investment for the pilot civilian plant was 1.33 billion RMB.[69] This included 17 sub-projects. In addition, the cost for startup testing has been estimated at 500–700 million RMB. There were also a number of other miscellaneous costs to bring the plant into operation. Overall, the reprocessing plant is estimated to have cost about 2-2.2 billion in 2005 RMB (2.9-3.2 billion 2014 RMB, or $830-910 million 2014 dollars, if converted at purchasing power parity).[70] The Chinese government provided the funding without any requirement for the project to pay interest or provide a return on investment. Chinese experts basically accept the high end of the range above, 2.2 billion RMB (in 2005 prices, 3.2 billion RMB in 2014 prices), as the total cost of a similar plant.

68 Kang Li, "Overview of Economics of Nuclear Reprocessing Engineering in China," (presentation, Harvard-Peking University Workshop on Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011).

69 Zhang Xiaodan and Zhang Yijian, "Development of China's Reprocessing Technology and Status of Pilot Plant ," China Nuclear Science and Technology Progress Report: the industrial applications of nuclear technology, vol.1, November 1999. Beijing (in Chinese).

70 Hu Xiaodan and Zhang Yijian, "China's reprocessing technology development and the pilot plant construction and adjustment status," *China Nuclear Science and Technology Progress Report: Nuclear technology application* (in Chinese), vol. 11 (2009). Inflated to 2014 using GDP deflators for China from 2005 to 2014; World Bank, "Inflation, GDP deflator (%)" (2015), http://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG (accessed September 4, 2015). The dollar figures, as with other dollar figures in this report, were reached by converting in the year of the original estimate using purchasing power parity (PPP) exchange rates, and then inflating to 2014 using OMB GDP deflators. The OECD estimate of the PPP yuan-dollar exchange rate in 2005 was 2.858; the OMB deflator to bring this to 2014 dollars is 1.1835. See OECD, "OECD.Stat: PPPs and Exchange Rates (2015), https://stats.oecd.org/Index.aspx?DataSetCode=SNA_TABLE4 (accessed September 4, 2015).

The actual cost of building another plant similar to the pilot reprocessing plant today would likely be higher than this figure. The estimated cost in 2005 included the nominal expenditures each year from the 1993 construction approval to the 2005 completion of the facility, and did not include interest during construction. (See Box 5.1, "The Effect of Interest During Construction.") In addition, the pilot plant shared some buildings with the former military reprocessing plant, and thus costs for those facilities, along with land fees for the site, were not included, which reduced the construction cost around 5 percent.[71] Moreover, the 2005 cost estimate did not include all the costs that have been incurred in the decade since then (including costs for a number of modifications, whose total will depend on the complexity of the changes). No estimate of those costs is publicly available. Nor did it include the expenses incurred in the preparation and application stages from the project's official approval in 1986 to its construction approval in 1993, which ranged from several million RMB to 100 millon RMB.

As mentioned earlier, by 2005 the cost estimates had been revised twice during construction. Early estimates were only a fraction of the eventual total cost. The major reasons for the cost increases and construction delays include:

- China lacked experience in building civilian reprocessing facilities. Given the sensitivity of reprocessing techniques, little could be learned from other countries. Moreover, the higher requirements for engineering quality and safety (compared to previous military efforts), coupled with the complex design, made the construction more difficult and increased the capital cost.
- The pilot plant was originally expected to use some existing facilities for water, electricity, steam, compressed air, and reagents. However, the construction project had to build new facilities to meet the new requirements of stricter safety and nuclear management standards.
- The materials and labor prices increased rapidly during the construction.
- Often, applicants for a project initially underestimate project cost to facilitate getting the government's approval; this may have happened in this case.

71 Communication with a CNNC expert, December, 2015.

3.2 *Chinese Estimates of the Capital Costs of Larger Reprocessing Plants*

How does one estimate the cost of a much larger facility from the costs of the Chinese pilot plant? This chapter describes the approach Chinese experts take to estimating the cost of commercial-scale reprocessing facilities, which is based on extrapolating from the experience with the pilot reprocessing plant.[72]

The design and construction of a commercial reprocessing plant is a very difficult and complex engineering project. China's reprocessing technology is relatively backward and its process for building its own commercial reprocessing plant project is still at a very early stage. The government has approved the early stages of site preparation for the 200 tHM/yr plant, but at this writing (late 2015) full-scale construction had not begun and the project's future remained uncertain. The 800 tHM/yr plant is not yet approved. No detailed official cost estimates for the 800 tHM/yr and 200 tHM/yr reprocessing plants are publicly available.

3.2.1 *Projected Capital Costs for a 200 tHM/yr Reprocessing Plant*

As a demonstration reprocessing project, the 200 tHM/yr reprocessing plant would, like the pilot plant, be intended to develop and improve the technology. To build such a facility, China would need to study and test the feasibility of the enlarged (or replicated) equipment and design. This could result in some problems arising during design and construction.

CNNC experts often apply the common technique of exponential scaling to estimate the cost of a larger plant based on a smaller one. In this approach, the capital cost, C, of a hypothetical facility with capacity M is related to an existing facility with capital cost C_O and capacity $M_{O,}$ with the scaling factor represented by γ:

$$C/C_O = (M/M_O)^{\gamma}$$

The scaling factor γ is typically between 0.6 and 1.0. Based on experience, if the production capacity of a hypothetical facility is between half as big and twice as big as an existing facility, Chinese experts typically use a scaling factor γ of 1.0. If the scale ratio is

72 Li, "Overview of Economics of Nuclear Reprocessing Engineering in China."

significantly larger but less than 50, and the increased capacity is dependent mainly on enlarging the equipment size, Chinese experts typically use a scaling factor in the range of 0.6-0.7.[73]

Considering that the 200tHM/yr medium-scale plant would have a capacity only four times the capacity of the pilot plant, it would be close to the first case (i.e. $\gamma = 1.0$). But the factor of four scale-up is a significant step beyond just a doubling in capacity. In this case, a value of $\gamma = 0.9$ is probably reasonable.

The capital cost estimates below for a 200 tHM/yr reprocessing plant are based on the assumption that, as with the pilot plant, there would be no cost for the land and no associated fees, and the government would provide the funding without any charge for interest or return on investment.

Using this exponential extrapolation method based on the 50 tHM/yr pilot plant, a preliminary cost estimate would be:

$$C_{200} = C_{50} * (200/50)^{0.9}$$

Where C_{200} is the capital cost of the 200 tHM/yr demonstration plant; C_{50} is the capital cost of the 50 tHM/yr pilot plant, which as discussed above was about 3.2 billion in 2014 RMB ($910 million in 2014 dollars). This suggests a capital cost for the 200 tHM/yr facility, C_{200}, of 11.3 billion in 2014 RMB ($3.2 billion in 2014 dollars).

However, the 200 tHM/yr plant is still an R&D project. Based on past experience with comparable R&D nuclear engineering projects (e.g. the pilot plant and CEFR projects), the final cost may well grow substantially compared to these early estimates. The huge uncertainty associated with R&D and demonstration projects is one major reason that costs might rise.

73 Similarly, the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) used a scaling factor of 0.6 to estimate the capital costs of reprocessing plants ranging from 600 tHM/yr to 2600 tHM/yr. See OECD/NEA, *The Economics of the Back End of the Nuclear Fuel Cycle* (Paris: OECD/NEA, 2013), p. 81. A recent DOE study argues that the exponent might shift, from a small value for small plants (which would have large economies of scale in scaling up) to a value close to one for large plants (which would have fewer remaining economies of scale available). See D.E. Shropshire, K.A. Williams, J.D. Smith, B.W. Dixon, M. Dunzik-Gougar, R.D. Adams, D. Gombert, J.T. Carter, E. Schneider, and D. Hebditch, Advanced Fuel Cycle Cost Basis, INL/EXT-07-1207, Rev. 2 (Idaho Falls: Idaho National Laboratory, December 2009), pp. F1-6-F1-10.

3.2.2 *Projected Capital Costs for an 800 tHM/yr Reprocessing Plant*

CNNC experts use the same methodology to estimate the capital cost of an 800 tHM/yr commercial reprocessing plant. If China built the plant using its own technology, it would expand the plant capacity by both increasing the size of individual pieces of process equipment and introducing multiple production lines. In this case, with a plant 16 times the size of the pilot plant, CNNC experts would typically use a scaling factor of 0.6–0.7. But if the increased capacity is mainly achieved by introducing multiple production lines, the scaling factor should be higher. Overall, a scaling factor of 0.85 could be appropriate.[74]

As with the 200 tHM/yr facility, the cost estimate for an 800 tHM/yr reprocessing plant does not include land fees or the costs of facilities outside the plant, including transportation and utilities, and assumes that the funding was provided by the government without any interest or return on investment.

Based on the 50 tHM/yr pilot plant, a preliminary estimate cost for an 800 tHM/yr plant would be:

$$C_{800}=C_{50}*(800/50)^{0.85}$$

Here, C_{800} is the capital cost of the 800 tHM/yr plant; C_{50} is the capital cost of the pilot plant (about 3.2 billion in 2014 RMB, or $910 million in 2014 dollars), leading to an estimate of 34 billion in 2014 RMB ($9.6 billion in 2014 dollars). As discussed below, this figure is consistent with the experience of British and French reprocessing plants at that scale, though substantially lower than the more recent experience in Japan.

This estimate of the potential cost of an indigenously designed 800 tHM/yr reprocessing plant is dramatically lower than public reports of the price offered by France to build a reprocessing plant, reported to be in the range of €20–€25 billion ($25-$31 billion in 2014 dollars).

Some Chinese experts argue one major reason for the lower price in China would be the lower labor cost in China than in developed countries. Labor, however, is not a major driver of the capital cost of reprocessing plants even in developed countries where labor costs are high. In the case of Britain's Thermal Oxide Reprocessing Plant (THORP), for

74 As discussed later in this report, a range of other exponents for scaling have been used in international studies, but this is the figure suggested by Chinese experts for scaling for the 800 tHM/yr plan.

example, just under 13,000 person-years of labor went into construction and testing. Even if one assumes that wages were, on average, twice the United Kingdom average at the time, the total would come to roughly 11 percent of the total capital cost.[75]

3.2.3 Uncertainties of the Scaling Approach

Arguably, the scaling factor might be even higher than the 0.85 used above. For example, an authoritative study concluded that the scaling factor was about 0.93 for aluminum reduction facilities, which are expanded by introducing multiple pot lines rather than by an expansion in the size of individual process equipment.[76] These facilities are comparable. China converted its Guangyuan military reprocessing plant into an aluminum reduction plant and its own reprocessing plant would be based mainly on modular modes through multiple production lines.[77] Additionally, China's prior experience with the pilot plant demonstrates that an expansion in the size of individual process equipment would be limited by the risk of plutonium criticality accidents.[78] If we assume that the scaling factor γ is 0.93 (instead of 0.85 as used above), then the capital cost would increase by about 25 percent.

The actual capacity of the pilot plant creates another element of uncertainty in these cost estimates, which are based on its design capacity of 50 tHM/yr. It is not clear that the pilot plant will ever reach 50 tHM/yr. So far it has processed less than a ton of spent fuel, and CNNC recently indicated that it planned to reprocess a total of 50 tons of spent fuel over three years—one third the design rate.[79] If we assume that the actual capacity of the pilot plant is about one third of the design capacity, then the capacity of an 800 tHM/yr plant would be an even larger multiple of the capacity of the pilot plant, and the capital cost estimate for an 800 tHM/yr plant would more than double.

There are other important uncertainties as well. As noted earlier, the costs of the pilot plant do not include land fees or the cost of facilities available at the old military reprocessing plant, which would have to be built new at a new facility, adding perhaps 5 percent to the capital cost. Moreover, as Chinese experts have emphasized, China's reprocessing technology

75 Average earnings in the United Kingdom in 1992 were reportedly £12,000/year; at twice this rate, the total number of man-hours required for THORP construction would cost £309 million. This represents about 11 percent of the estimated cost of £2.85 billion. http://www.measuringworth.com/m/datasets/ukearncpi/ (accessed January 4, 2016).

76 Frederick T. Moore, "Economies of Scale: Some Statistical Evidence," *Quarterly Journal of Economics*, Vol.73, Issues 2 (1995): pp.232-245, https://msuweb.montclair.edu/~lebelp/MooreEcsScaleQJE1959.pdf (accessed January 4, 2016).

77 Hui Zhang, "China's HEU and Plutonium Production and Stocks."

78 Communication with CNNC nuclear experts in Beijing, November 2014.

79 Communication with CNNC nuclear expert in Beijing, November 2014.

is still backward. If the proposed commercial plant used more advanced equipment and technology (either domestic or imported), the capital cost could be significantly higher. Furthermore, Chinese safety, security, and environmental requirements have become more stringent (particularly after the 2011 nuclear accident in Japan), and this could increase costs of a future facility.

Overall, the cost of an 800 tHM/yr reprocessing plant could turn out to be as much as two to three times higher than extrapolations from the pilot plant suggest—which would be comparable to Japan's experience, as discussed below. In fact, the capital costs of the pilot plant and CEFR both ended up in the range of three to four times the original estimates.[80] As discussed below, Japan has had a similar experience with its Rokkasho reprocessing plant.

Moreover, as noted above, CNNC agreed in 2010 to offer €10 billion (about $12.5 billion in 2014 dollars) to AREVA for an 800 tHM/yr reprocessing plant when AREVA's asking price was about €20 billion, and AREVA rejected the offer.[81] This could indicate that the minimum capital cost for China to build an 800tHM/yr reprocessing plant would be in the range of $12.5 billion. It seems clear that if Chinese policymakers were confident that they could build an 800 tHM/yr plant for much less than the price offered by the French, they would not have recently signed an MoU with the French to move forward on the French plant.[82] The low cost estimate above may not accurately reflect the current Chinese government's understanding of how much it would cost China to build a commercial-scale reprocessing plant.

3.3 Capital Cost of the China Experimental Fast Reactor

Based on a presentation given in 2013 by a leader of the fast reactor division of CIAE, estimates of the total capital cost of the CEFR increased substantially, twice, during the plant's construction. Initially, the total capital cost was projected to be about 680 million RMB. This figure roughly doubled, to 1359 million RMB, after a review of the preliminary design. After the detailed design was finished, the capital cost finally settled at 2516 million RMB ($387 million), roughly 3.7 times the original estimate.[83]

80 For CEFR cost, see: Yang, "Economic Issues of Fast Reactor in China"; pilot plant cost based on communication with a CNNC expert, November 2014.

81 "China: Is France to Blame for CNNC's Back-End Problems?" *Uranium Intelligence Weekly*.

82 CNNC, "CNNC and AREVA Nuclear Cooperation in Spent Fuel Reprocessing," April 26, 2013, http://news.bjx.com.cn/html/20130426/431263.shtml (accessed January 4, 2016).

83 Yang, "Economic Issues of Fast Reactor in China." While the speaker did not mention the year of the final capital cost, we can infer based on the exchange rate (1$=6.5 RMB) between U.S. dollars and Chinese RMB that it was around 2011 when China also announced the CEFR was in operation.

Table 3.1 shows the cost breakdown in detail. The unit cost of the CEFR is about $19,357 per kilowatt. In 2011, the unit cost of an AP-1000 in China was reportedly about $1,940 per kilowatt, one tenth as large, according to an estimate by the president of SNPTC, the developer of China's AP-1000.[84] While small, first-of-a-kind experimental facilities can be expected to have high per-unit costs, even in serial production, many analysts expect the capital cost of fast reactors to be higher than that of LWRs of the same generation, as discussed below.

Table 3.1: **The Overnight Capital Cost of the CEFR**

Item	Cost (RMB)	Ratio
Civil and erection cost	**1,639,528,800**	**65.15%**
Civil engineering	335,053,400	13.31%
Equipment procurement	1,002,590,100	39.84%
Erection engineering	301,885,300	12.00%
Indirect cost	**695,842,200**	**27.65%**
In design	109,851,100	4.37%
First loading fuel	**115,989,500**	**4.61%**
Preparation R&D	**65,017,400**	**2.58%**
Total	**2,516,377,900**	100.00%

Source: Yang, "Economic Issues of Fast Reactor in China."

The CIAE expert emphasized that the major reasons for the increase in the capital cost of the CEFR include:[85] (a) changes in the technical configuration and key system during the construction; (b) a lack of engineering management experience, particularly in organizing and coordinating the development of an integrated, pool-type, fast reactor design; (c) delays in construction from the reasons listed above and others. All of these factors led to increases in the indirect costs.

84 "China: Progress on FBR/HTGRs, But Obstacles Remain," *Uranium Intelligence Weekly.*

85 Yang, "Economic Issues of Fast Reactor in China."

4. The Cost of Reprocessing: International Experience

As a committee of the U.S. National Academy of Sciences has argued, the real costs of building and operating reprocessing plants in the past "provide the most reliable basis for estimating the costs of future plants."[86] Only a small number of large commercial reprocessing plants have been built in the world, however. In this chapter, we will describe the costs of construction and operation of large commercial reprocessing plants in Japan (the Rokkasho Reprocessing Plant, or RRP), in France (UP2 and UP3 at La Hague), and in the United Kingdom (the Thermal Oxide Reprocessing Plant, or THORP, at Sellafield). Russia also operates a large reprocessing plant at the Mayak Production Association in the town of Ozersk, but this plant was built in Soviet times, was fully integrated with military activities, and its full costs are neither well documented in the public literature nor likely to be comparable to those of a future commercial plant in China. India operates some smaller reprocessing plants, but they were built with considerable secrecy over costs, so their costs are also not well documented or likely to be comparable to costs of a commercial Chinese reprocessing plant. This chapter also briefly discusses recent U.S. and international estimates of the cost of building and operating future reprocessing plants, though these are merely paper estimates rather than real experience.

Although the past experience of other countries offers valuable lessons for China's future plans, international comparisons should be approached with caution. In addition to the small number of cases for comparison, the conditions in the United Kingdom and France in the 1980s or in Japan since the 1990s are quite different from those that can be expected in China in the period around 2020 or beyond, when a large-scale commercial reprocessing plant might be built. (For a discussion of the uncertainties in making comparisons across countries and times, see the appendix, "Effects of Currency Exchange Rates and Inflation.") Nevertheless, other countries' real experience is an important input into understanding what reprocessing might cost in China.

86 U.S. National Research Council, Committee on Separations Technology and Transmutation Systems, *Nuclear Wastes: Technologies For Separation and Transmutation* (Washington, D.C.: National Academy Press, 1996), p. 421.

The most important costs associated with reprocessing spent nuclear fuel are:

- the capital cost to build the facility (including whatever rate of return is assumed for that capital investment);
- the cost to operate the facility (including whatever capital additions may be required over the life of the plant); and
- the ultimate cost of decommissioning the plant.

For most plants it has proved to be necessary to make additional capital investments during the life of the plant to refurbish, maintain, and replace equipment within the plant. These are sometimes referred to as Post-Operational Capital Additions (POCA). These are less well-documented in the public literature, in most cases, and some estimates either ignore these costs or fold them into operations and maintenance costs.

This chapter provides estimates of all three of the primary categories of cost where practicable. In some of these cases, detailed cost estimates (particularly with respect to operating costs) were considered commercially proprietary and were not publicly released. In all three of these countries, however, public inquiries or investigations have revealed fairly detailed and reasonably authoritative estimates of many of the costs of these facilities.

4.1 The Rokkasho Reprocessing Plant

The reprocessing plant at Rokkasho-mura in Japan, built with French help to a design modeled in large part on the French UP3 plant, is the most recent commercial reprocessing plant to be built. After many years of delays, it has been essentially complete for years, though it has never operated for more than pilot testing. In late 2015, Japan Nuclear Fuel Limited (JNFL), the organization responsible for its construction, again delayed operation of the plant, this time until 2018.[87] The plant is designed for a capacity to process 800 tons of heavy metal in spent fuel each year.[88]

87 See Japan Nuclear Fuels Limited, "Schedule Change of Completion of Rokkasho Reprocessing Plant and MOX Fuel Fabrication Plant" (Tokyo: JNFL, November 16, 2015), http://www.jnfl.co.jp/english/topics/151116-1.html (accessed January 4, 2016).

88 For a useful overview of the issues surrounding reprocessing in Japan, see Tadahiro Katsuta and Tatsujiro Suzuki, *Japan's Spent Fuel and Plutonium Management Challenges* (Princeton, N.J.: International Panel on Fissile Materials, September 2006), http://ipfmlibrary.org/rr02.pdf (accessed January 31, 2015).

Capital Costs. JNFL estimates the capital cost of the reprocessing plant at ¥2.1930 trillion.[89] If converted using PPP figures and inflated to the present from the 2007 date when this estimate was first offered, this amounts to approximately $20.3 billion (2014$).[90] Converted at market exchange rates rather than PPP (as may be appropriate, given the significant proportion of the cost that was sourced internationally), the cost would be $21.8 billion.[91]

As high as this figure is, it seems likely to be an underestimate. The estimate has remained constant for seven years; for it still to be correct would require that in that entire period—during which many startup delays and additional problems have occurred—there have been no additional costs that were not expected in 2007. Moreover, the estimate appears to represent the number of yen spent during the years of construction, rather than the number of yen adjusted to 2007 prices, so realistic accounting for inflation would likely bring the cost still higher—particularly given the higher-than-average inflation of nuclear construction costs.

Operating Costs. Since the Rokkasho reprocessing plant has never operated (except for initial tests), its future operating costs are uncertain. Under Japanese law, to ensure that sufficient funds are set aside, the government is required to estimate the operating costs for reprocessing.

Data presented by Japan Atomic Energy Comission (JAEC) in 2012 break down the annual projected costs of reprocessing and associated activities for each year from 2012 through the plant's eventual decommissioning. During the main period of plant operations, total operating costs in a typical year are projected to be in the range of ¥160 billion (over $1.5 billion 2014$).[92] This total, however, includes both reprocessing and other activities, such as transport of vitrified waste to a disposal site and disposal operations. Reprocessing itself accounts for over 90 percent of the total life cycle cost of the package of

89 JNFL, "Overview of the Facility," October 2014 update, http://www.jnfl.co.jp/jnfl/establishment.html (in Japanese, accessed December 21, 2014). This figure has remained unchanged since 2007.

90 PPP conversion for 2007 is 120.3 yen to the dollar; inflating from 2007 dollars to 2014 dollars requires multiplying by 1.11.

91 The three-year average of the currency exchange rate centered on 2007 is 0.0110 yen to the dollar. Historical rates are available from many sources, including Oanda, "Historical Exchange Rates," http://www.oanda.com/lang/en/currency/historical-rates/ (accessed December 21, 2014).

92 JAEC, "Kakunenryou Saikuru no Shoryou/Keizaisei Hyoka Ni Tsuite," (Regarding Economic Assessments and Various Data on the Nuclear Fuel Cycle), (Tokyo: JAEC, June 11, 2012), http://www.aec.go.jp/jicst/NC/tyoki/hatukaku/keisan/kaku_cycle.pdf (accessed February 1, 2015), p. 57. The authors are grateful to Tatsujiro Suzuki for pointing out this reference and for other helpful discussions of available data on the costs of the Rokkasho reprocessing plant. PPP conversion from yen to dollars for 2011 (the original date of JAEC estimates) is 107.45; inflating 2011 figures to 2014 requires multiplying by 1.051.

activities, and operating costs are by far the largest portion of that total life-cycle cost, so it is reasonable to assume that the operating costs of reprocessing account for a similar proportion of the ¥160 billion in total operating costs, amounting to ¥145-150 billion in a typical year. If the plant was operating at its full design capacity of 800 tHM/yr, and we take the lower end of the range, this would amount to ¥181,000/kgHM ($1790/kgHM, 2014$).

Decommissioning Costs. Japan estimates that decommissioning of Rokkasho will cost ¥1.54 trillion (2011 yen, over $15 billion in 2014 dollars), representing some 70 percent of the initial capital cost of the facility.[93] Those costs, however, will be incurred decades from now, reducing their present value substantially. If one assumes that decommissioning will begin after 50 years, and if the discounting rate was 3 percent, the present value of this cost would be ¥350 billion (over $3.4 billion in 2014 dollars).

Total Costs. JAEC estimates that the total cost of the Rokkasho reprocessing plant over its life, including capital, operating, and decommissioning costs, along with some allowance for interest during construction, will be ¥10.81 trillion ($106 billion 2014$), for reprocessing 32,000 tons of spent fuel. With neither discounting of future costs nor any allowance for return on investment, this would amount to nearly ¥340,000/kgHM (over $3,300/kgHM, 2014$). When the other costs of this back end approach, including transport and final disposal, were included, the JAEC study projected a total cost of ¥370,000/kgHM (over $3,600/kgHM, 2014$).[94] Clearly, even without any allowance for return on investment, the costs of reprocessing at Rokkasho are far beyond the $1,000/kgHM estimate used in some studies.

4.2 The Thermal Oxide Reprocessing Plant

Britain's Thermal Oxide Reprocessing Plant (THORP) began construction in 1985, and the first radioactive fuel was sheared and dissolved in 1994.[95] The plant has had substantial difficulties, including a major leak that shut it down for years, and it is expected to be closed in a few years when its current contracts are completed. Its builder, British Nuclear Fuels, Limited (BNFL), went bankrupt and the facility is now owned by Britain's National Decommissioning Authority (NDA), with a focus, as the name implies, on closing out and

93 Technical Subcommittee, "Estimation of Nuclear Fuel Cycle Cost," p. 17.

94 Technical Subcommittee, "Estimation of Nuclear Fuel Cycle Cost." p. 37.

95 For a summary of the THORP experience, see Martin Forwood, *The Legacy of Reprocessing in the United Kingdom* (Princeton, N.J.: International Panel on Fissile Materials, July 2008), http://ipfmlibrary.org/rr05.pdf (accessed January 31, 2015). For an account providing a more detailed history of the decision-making around THORP, showing how supporters managed to structure decisions so that it became ever more difficult to turn back, see William Walker, *Nuclear Entrapment: THORP and the Politics of Commitment* (London: Institute for Public Policy Research, 1999).

decommissioning this and other facilities. While there has been considerable controversy over its annual reprocessing capacity (arising from its frequent failure to meet targets), we will use its original design capacity of 900 tHM/yr, which is also the most the facility ever reprocessed in a single year.

Capital Costs. BNFL reported that the THORP facility and "directly related" projects cost some £2.85 billion to build. This is an estimate made in 1993, covering a spending period of 1983-1992.[96] This amounts to nearly $6.8 billion 2014$, roughly one-third the reported cost for construction of the similarly sized Rokkasho reprocessing plant.[97] In another study, BNFL provided an estimate that amounted to £3.07 billion for THORP and directly related facilities ($7.8 billion 2014$).[98]

Operating Costs. Neither BNFL nor its successors have ever provided an official figure for THORP's operating costs, but before THORP began operating, BNFL provided a public estimate that a similar plant would have an annual operating cost of £214 million ($546 million 2014$), or over $600/kgHM if the plant operated at full capacity.[99] BNFL in this period frequently underestimated future costs, and indeed, on a per-kilogram basis BNFL later concluded that costs were higher than originally anticipated, and asked for additional payments from customers to cover these higher costs.[100] Nevertheless, to be conservative, we will rely on this early BNFL estimate. This is again roughly one-third of the costs estimated above for the Rokkasho reprocessing plant.

96 British Nuclear Fuels Limited, *The Economic and Commercial Justification for THORP* (Risley, UK: BNFL, 1993), p. 22. BNFL states that the "construction cost of THORP, spread over the ten years 1983-1992, equates to around £1.9Bn. However, taking account of other projects which are directly related to THORP, the overall capital cost of the programme was around £2.85 Bn."

97 The PPP conversion from 1993 pounds to dollars is 0.628; inflating from 1993 dollars to 2014 dollars requires multiplying by 1.50. If, instead, one inflates on the basis of the years in which the money was spent, the 2014$ figure would be closer to $8 billion. These estimates do not include subsequent capital investments that proved to be necessary to operate the plant. In 2000-2001, BNFL asked customers to cover £100 million in additional capital costs not initially anticipated. See, for example, Ann MacLachlan, "BNFL, Overseas Customers Agree on New Reprocessing Contract Terms," *Nuclear Fuel*, October 15, 2001. Similarly, BNFL encountered large additional costs to fix various problems with the plant, particularly after the 2005 leak that shut the plant for several years.

98 Organization for Economic Cooperation and Development, Nuclear Energy Agency, *The Economics of the Nuclear Fuel Cycle* (Paris: NEA, 1994), p. 113. This includes all listed costs except those for transport of spent fuel to the facility and transport and disposal of wastes. These are in 1991 money values (p. 23). The 2014$ figure is significantly higher because the pound was worth slightly less in 1991 than in 1993 and there was additional U.S. inflation between 1991 and 1993. The PPP conversion from 1991 pound to dollars 0.617; inflating from 1991 dollars to 2014 dollars requires multiplying by 1.57.

99 OECD/NEA, *The Economics of the Nuclear Fuel Cycle*, p. 113. This includes all the listed costs except transport to the reprocessing plant and transport and disposal of wastes.

100 See, for example, MacLachlan, "BNFL, Overseas Customers Agree on New Reprocessing Contract Terms."

Decommissioning Costs. BNFL originally estimated that decommissioning a facility like THORP would cost 30 percent of the original capital cost to build the facility, a total of £911 million (amounting to $2.3 billion 2014$).[101] Estimates of the cost of decommissioning the Sellafield site have ballooned since then to £70 billion (over $100 billion 2014$), compared to a 2002 estimate of £27.5 billion ($56 billion 2014$).[102] But there are many facilities at Sellafield in addition to the THORP plant, and the NDA has not broken out a specific THORP decommissioning cost estimate in recent years. One can assume, however, that the currently projected costs of decommissioning THORP are substantially higher than BNFL's original estimates.

Total Costs. In addition to initial capital cost, operating cost, and decommissioning cost, BNFL originally projected that there would be £567 million (over $1.4 billion 2014$) in refurbishment costs (sometimes called post-operational capital additions) over the life of a plant of this type.[103] In the end, actual capital additions have been substantially higher than this, but as far as the authors are aware, a complete accounting of these has not been made public. After the 2005 leak, for example (which was contained in a cell in the plant), there were major engineering modifications. Combining the original estimates of refurbishment costs with the initial capital cost, the annual operating cost, and the decommissioning cost, BNFL's early estimates suggest that operating a plant of this type for 40 years would cost over $33 billion (2014$) over its life-cycle (again, roughly one-third the cost of the Rokkasho reprocessing plant)—if there was no allowance for any return at all on investment, and no discounting of decommissioning costs. If it had managed to operate at full capacity for the entire period, this would have come to something just under $920/kgHM. THORP has not operated at anything resembling full capacity, however. It is expected to have reprocessed roughly 10,000 tons of spent fuel by the time it closes in 2018.[104] Considering an operating period from 1994-2018, if the real costs had not grown over BNFL's initial estimates, the cost per kilogram would be in the range of $2400/kgHM (2014$, again with no allowance for any return on investment and no acknowledgement of the reality that costs have been higher than originally estimated).

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101 OECD/NEA, *The Economics of the Nuclear Fuel Cycle*, p. 113. These calculations use 1991 money values, i.e. a PPP conversion of 0.617 and inflation from 1991 to 2014 dollars requires multiplying by 1.57.

102 For the £70 billion figure, see, for example, "Sellafield £70bn Clean-Up Costs 'Astonishing,' MPs Say," BBC News, February 11, 2014. The £27.5 billion figure is from U.K. Department of Trade and Industry, *Managing the Nuclear Legacy* (London: DTI, July 2002), p. 18, cited in Forwood, *The Legacy of Reprocessing in the United Kingdom*, p. 25. The PPP conversion from pounds to dollars for 2002 is 0.640; to convert from 2002 to 2014 dollars requires multiplying by 1.27.

103 OECD/NEA, *The Economics of the Nuclear Fuel Cycle*, p. 113. Again, this includes all listed costs except those associated with transporting fuel to the plant or transport and disposal of wastes.

104 Francis Livens and Janet Wilson, "Update on Spent Fuels and Nuclear Materials," CoRWM Doc. 155 (London: U.K. Committee on Radioactive Waste Management, March 11, 2014).

4.3 UP2-800 and UP3

France currently operates two large reprocessing plants at the La Hague site, UP2-800 and UP3, each with a nominal capacity in the range of 800 tHM/yr. Both plants were authorized in 1981; UP3 began operation in 1989, and UP2-800 in 1994.[105]

Capital Costs. AREVA has indicated that the total construction cost of UP3 and UP2-800 was €19.5 billion (2010 euros—over $24 billion 2014$).[106] If this cost was roughly equally divided, this suggests a cost for an 800 tHM/yr plant of roughly $12 billion (2014$). The difference from THORP may relate primarily to currency conversions and inflation; a 2000 estimate, also official, of 37 billion French francs for construction of UP2-800 comes to only $8 billion 2014$.[107]

Operating Costs. Less current data is available on the operating costs of these facilities. The 2000 French study concluded that the operating costs for UP2-800 were 4000 French francs per kilogram in its early years, but would likely decline to approximately 3000 francs per kilogram after 2000 (roughly $640/kgHM 2014$), if the plant operated at full capacity.[108] Similarly, a recent Nuclear Energy Agency (NEA) study reports an estimate in the range of $900 million per year for both UP2-800 and UP3 together (2010$, equivalent to $960 million in 2014$); at full capacity, this would amount to $600/kgHM (2014$).[109]

105 UP2-800 was a follow-on to an earlier facility, UP2-400, now being decommissioned; that explains why this facility labeled UP2 started up after UP3. For a discussion of the history of these facilities and others at La Hague and Marcoule, see Mycle Schneider and Yves Marignac, *Spent Nuclear Fuel Reprocessing in France* (Princeton, N.J.: International Panel on Fissile Materials, April 2008), p. 19.

106 See Cour des Comptes, *The Costs of the Nuclear Power Sector: Thematic Public Report* (Paris: Cour des Comptes, January 2012), p. 34. 2010 PPP conversion for France is 0.86, which is then multiplied by 1.0715 to inflate 2010 dollars to 2014 values.

107 This was part of the analyses done to support Jean-Michel Charpin, Benjamin Dessus, and René Pallat, *Economic Forecast of the Nuclear Power Option: Report to the Prime Minister* (Paris: Office of the Prime Minister, July 2000). See Yves Marignac, "Briefing: Results of the 'Charpin-Dessus-Pellat' Mission *Economic Forecast Study of the Nuclear Power Option*" (Paris, France: World Information Service Energy-Paris, January 18, 2001), p. 7. Marignac was one of two authors of the supporting study to the Charpin et al. study, on the economics of the existing nuclear power infrastructure in France. The study specifies that it is using 1999 money values. PPP for France in 1999 is 0.956, but this is a conversion from Euros rather than from Francs; the fixed Euro-Franc rate adopted when the Euro began was 6.56; inflating from 1999 to 2014 requires multiplying by 1.35.

108 Marignac, "Briefing: Results of the `Charpin-Dessus-Pellat' Mission," p. 7.

109 Organization for Economic Cooperation and Development, Nuclear Energy Agency, *The Economics of the Back End of the Nuclear Fuel Cycle* (Paris: OECD/NEA, 2013), p. 82.

Decommissioning Costs. AREVA estimates the cost of decommissioning UP2-800 and UP3 as €4.26 billion ($5.3 billion 2014$).[110] This amounts to 22 percent of the original cost of construction—a relatively low fraction. The French accounting review agency, the Cour des Comptes, warns that other decommissioning projects increased in cost as they moved from projections to implementation. As with THORP and the Rokkasho reprocessing plant, however, this expense will be incurred decades in the future.

Total Costs. As with Rokkasho and THORP, UP2-800 and UP3 have required investments in refurbishment in addition to initial capital cost, operating cost, and projected decommissioning cost. Unfortunately little data on these post-operations capital additions is publicly available. If, as in the case of THORP and Rokkasho, one assumes that one of these facilities would operate for 40 years, and adds initial capital cost, operating cost, and decommissioning cost, the total life-cycle cost (with no allowance for return on capital or for refurbishment) would be in the range of $30 billion (2014$, using the smaller of the two capital cost figures above). If one assumes operation at full capacity for the entire period (an unrealistic assumption) this would amount to roughly $930/kgHM (2014$). But UP2-800 and UP-3 have often processed much less than their licensed capacity, in large part because their foreign contracts are largely completed and few further foreign contracts appear to be forthcoming. From 2001–2006, the two plants operated at about 62 percent of their licensed capacity, and there is little expectation this will increase. If these plants operated at that rate for 40-year lives, the per-kilogram costs would be closer to $1100/kgHM, even with the unlikely assumption that operations costs would be reduced by the same fraction. This again makes no allowance for return on investment. More realistic assumptions would lead to far higher costs, as discussed below.

110 Cours des Comptes, *The Costs of the Nuclear Power Sector*, p. 103.

4.4 Would China's Experience Likely Be More Like Rokkasho, or Like THORP and La Hague?

Clearly, the costs of Rokkasho have been far higher than those France and the United Kingdom experienced in building their earlier reprocessing plants. Which is more likely to be similar to what China would experience?

On the one hand, one could make an argument that Rokkasho is a unique case, not likely to be representative. Issues from generally high costs in Japan to years of delay to the Japanese effort to use their own design for the vitrifier have driven up costs. None of these would necessarily apply to a plant built in China.

On the other hand, Rokkasho is the most recent large reprocessing plant to be built. It may be that real costs of construction for such plants have increased at a rate far higher than the rate of general inflation, so that it should be expected that new plants would have costs closer to those of Rokkasho than to those of THORP or La Hague. In most countries, inflation for construction generally has been substantially higher than the general rate of inflation. AREVA's proposed €20 billion price for a plant in China—much closer to the costs of Rokkasho than to those of La Hague—suggests that they suspect that this might be the case.

5. Projecting Unit Costs of Reprocessing in China

The per-kilogram cost of reprocessing at a particular facility depends primarily on:

- The cost to build the facility;
- The cost to operate and maintain the facility;
- The amount of spent fuel the facility will process (per year, and over its lifetime); and
- The interest or return on investment that must be paid on the capital invested (along with any taxes and insurance, in the case of private facilities).

Additional factors that affect the per-kilogram cost include any post-operational refurbishment or capital additions that may be needed during the facility's life, and the funds that must be set aside for decommissioning.

In general, the per-kilogram costs at smaller facilities will be higher than those at larger facilities, because the fixed portion of the capital and operating costs are spread over a smaller number of kilograms of fuel processed by the facility each year. Hence, this chapter will address projected costs for a 200 tHM/yr reprocessing plant and an 800 tHM/yr reprocessing plant separately.

Unfortunately, public information is not available on Chinese estimates of the likely operating costs for the 200 tHM/yr or 800 tHM/yr reprocessing plants. The Japanese estimate of the annual operating cost for the Rokkasho reprocessing plant is 7–8 percent of the facility's total capital cost.[111] Similarly, the British estimate of the operating cost of THORP (before operations began) was in the range of 7 percent of the expected capital cost at that time.[112] Estimates of the costs of building and operating the UP2 and UP3 facilities put the operating costs at only 4 percent of the capital costs, but as discussed above, the high capital cost of this estimate may reflect currency fluctuations more than a real difference in capital cost between these facilities and THORP.[113] The U.S. Congressional Budget Office

111 JAEC, "Regarding Economic Assessments and Various Data on the Nuclear Fuel Cycle."

112 OECD/NEA, The Economics of the Nuclear Fuel Cycle, p. 113.

113 OECD/NEA, The Economics of the Back End of the Nuclear Fuel Cycle (Paris: OECD/NEA, 2013), pp. 81–82.

estimated that the annual operating costs of a reprocessing plant in the United States would be 6 percent of the initial capital cost; for the purposes of this report, we will use this figure when more detailed information is not available.[114]

5.1 High and Low Estimates of Capital and Operating Costs

To summarize the discussions earlier in this report, extrapolating from the experience of the pilot reprocessing plant would lead to the following estimates:

- 200 tHM/yr plant: capital cost $3.2 billion; if operating costs were 6 percent of capital costs, they would be $190 million per year.
- 800 tHM/yr plant: capital cost of $9.6 billion; if operating costs were 6 percent of capital costs, they would be in the range of $580 million per year.

The experience of the construction of the British and French plants in the 1980s and early 1990s leads to capital cost estimates broadly consistent with these Chinese projections, though by some estimates, capital costs were more in the range of $8 billion for these 800 tHM/yr facilities. Operating costs of these plants was estimated to be in the range of $480-$550 million per year.

By contrast, the Japanese experience with the Rokkasho Reprocessing Plant and AREVA's commercial offers to China for construction of an integrated reprocessing and MOX plant in China both suggest a much higher cost. Generously, for modeling we might consider a higher-cost possibility of $20 billion for an 800 tHM/yr plant (lower than either the Rokkasho cost or the French offer to China), with an operations and maintenance cost comparable to estimates for Rokkasho, in the range of $1.5 billion per year. Extrapolating downward using the same scaling approach to the size of the 200 tHM/yr plant would suggest a capital cost of $5.7 billion, with an operating cost perhaps in the range of $340 million per year. Table 5.1 shows these high and low estimates for each plant, along with the costs of the alternative of 40-year storage of the same amount of fuel, assuming a storage cost of $200/kgHM.

114 Peter R. Orszag, "Costs of Reprocessing Versus Directly Disposing of Spent Nuclear Fuel," testimony to the Committee on Energy and Natural Resources, U.S. Senate, November 14, 2007.

Table 5.1: **High and Low Estimates of Reprocessing Capital and Operating Costs**

Plant	Capital cost	Operating cost	40-year cost	40-year dry storage cost
200 tHM/yr, Low	$3.20 B	$0.19 B	$10.80 B	$1.60 B
200 tHM/yr, High	$5.70 B	$0.34 B	$19.30 B	$1.60 B
800 tHM/yr, Low	$8.00 B	$0.48 B	$27.20 B	$6.40 B
800 tHM/yr High	$20.00 B	$1.50 B	$80.00 B	$6.40 B

It should be noted that this table does not include any of the costs of financing these facilities, of decommissioning the facilities, or of capital additions that are likely to be required during the lifetime of such facilities. Two key points can be seen from this table:

- Despite the important costs that are excluded, even the low estimates are far higher than the cost of storing the fuel that would be processed for the lifetime of the plant. The difference is in the range of billions for the modest-scale plant and tens of billions for the large plant.
- The differences between the high and low estimates for both capital and operating costs are large; the uncertainty in estimating the costs of these facilities is high.

5.2 *Financing a Reprocessing Plant in China and the Unit Cost of Reprocessing*

The cost per kilogram for a capital-intensive facility like a reprocessing plant depends on the financing charges. The CNNC has envisioned four scenarios for financing a commercial-scale reprocessing plant:[115]

- The Chinese government may simply provide the funds to build the facility to CNNC without requiring any interest or return on investment (effectively a 0 percent rate of return), as occurred with the pilot reprocessing plant.
- CNNC might finance the plant from the money in the reprocessing fund, discussed above. Since construction might begin before the fund had accumulated enough money to finance it, this might involve 20-30 percent of the capital cost being taken from the

115 Discussions with CNNC expert, late 2014.

fund and the rest being financed through commercial loans (typically at an interest rate in the range of 5-7 percent).

- A portion might be funded from government "management funds" and the rest from low-interest government-backed loans.
- CNNC might finance a portion of the construction from its own funds, with the rest from low-interest government-backed loans. (For its own investments, CNNC typically seeks something in the range of a 9 percent rate of return.)[116]

Of course, other variants are possible as well. All of the rates of return noted above are nominal rates. Finding the "real" rate above inflation is difficult, as both consumer inflation and GDP inflation in China have been volatile in recent years, but Chinese analysts often assume an inflation rate of 3 percent.[117]

It should be noted that even if funds provided by the Chinese government are "free" to the CNNC, they are not "free" for China as a whole. One way of thinking about the cost to a government is to consider that government's cost to borrow money. The rate the Chinese government pays on ten-year bonds averaged 3.7 percent from 2005–2015.[118] This is a nominal rate, however; subtracting China's GDP inflation over that period would make the real rate negative.[119]

Another approach is to consider the return on other investments the Chinese government could have made with the same money—the "opportunity cost" of using this money for this investment rather than a different investment. The amount the Chinese government spends is limited by its desire to avoid provoking domestic inflation, so money spent for one purpose means less money spent for other purposes. The Chinese government spends money with a number of goals, including expanding Chinese economic growth, and presumably seeks to maximize the return on its investments. Overall Chinese economic

116 CNNC has financed its projects in a variety of ways, including funding from the government; low-interest government-backed loans from Chinese banks; issuing bonds (which carry a somewhat higher yield than Chinese government bonds); and, in 2015, sold over $2 billion in equity shares, to help finance nuclear power plant construction. CNNC's investors will presumably insist on rates of return on investments of CNNC capital at least as high as those available from other firms facing similar risks elsewhere in the Chinese economy. For the CNNC's initial public offering (IPO), see Ansuya Harjani, "China's Biggest IPO Since 2011 Debuts With a Bang," CNBC, June 9, 2015, http://www.cnbc.com/2015/06/09/shares-of-china-national-nuclear-power-rocket-in-market-debut.html (accessed January 4, 2016).

117 Discussions with a CNNC nuclear expert, late 2014.

118 Trading Economics, "China Government Bond 10Y: 2005-2015," http://www.tradingeconomics.com/china/government-bond-yield (accessed September 5, 2015).

119 This depends heavily on the period considered, as annual GDP inflation in China in the last decade has ranged from less than zero to over 8 percent. For data on Chinese GDP inflation, see World Bank, "Inflation, GDP deflator (%)" (2015), http://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG (accessed September 4, 2015).

growth has been running at 7–8 percent in recent years in real terms, and the Chinese government now projects 6.5 percent annual growth for the next few years.[120] In most economies the average return on capital investment is somewhat higher than the rate of economic growth; hence a 8-10 percent real (above inflation) rate of return on investment to a particular firm would not be an unreasonable expectation.[121] Indeed, rates of return on capital in China in the last decade have usually been above 10 percent.[122]

For the purposes of this report, we will consider three real weighted average costs of capital for a reprocessing project: 0, 3, and 6 percent annually. The first reflects a CNNC perspective if the Chinese government provides full funding (as is reportedly planned for the 200 tHM/yr plant); the second reflects a plausible result of partial funding by CNNC with an expected internal rate of return in the range of 9 percent nominal (6 percent real, if 3 percent inflation is assumed) and the remainder financed with low-cost loans; and the last represents full financing by CNNC. For simplicity, we neglect Chinese corporate taxes and insurance; if those were included, and CNNC financed 50 percent of the project with its own internal equity and the rest with loans at a real rate of 3 percent, the resulting annual capital charge would be similar to that for the simple 6 percent real rate considered here.[123] We neglect examining returns on capital of 10 percent or greater, as exist for other projects in China, on the grounds that the reprocessing costs with such returns would be so high as to be prohibitive. Hence, even the highest of these rates is lower than what might be considered the "opportunity cost" of using this capital for this purpose rather than other purposes, discussed above.

The fraction of the original capital cost required each year for the combination of paying off capital and providing interest to lenders or returns to investors is known as the *fixed charge rate,* or FCR. For 0 percent financing and a 40 year life, this would simply be the capital cost of the facility divided by 40, or 2.5 percent per year. For 3 percent financing and a 40 year life, this amounts to 4.3 percent per year, and for 6 percent financing with the same facility life, the FCR would be 6.6 percent per year.[124]

120 Edward Wong, "China Aims for 6.5% Economic Growth Over Next 5 Years, Xi Says," *The New York Times*, November 3, 2015.

121 The rate of real Chinese GDP growth is somewhat controversial, as some analysts believe Chinese official figures to be inflated. The figures here are from U.S. Central Intelligence Agency, *World Factbook* (Washington, D.C.: CIA, 2015), https://www.cia.gov/library/publications/resources/the-world-factbook/geos/ch.html (accessed January 4, 2016). For an extensive discussion of the idea that the return on capital tends to be higher than the rate of economic growth, contributing to ever-increasing concentrations of wealth, see Thomas Piketty, *Capital in the 21st Century* (Cambridge, MA: Harvard University Press, 2014).

122 See, for example, Organization for Economic Cooperation and Development, *OECD Economic Surveys: China* (Paris: OECD, March 2015), http://www.oecd.org/eco/surveys/China-2015-overview.pdf, p. 26 (accessed January 4, 2016).

123 For a discussion of fixed charge rates including debt, equity, taxes, and insurance, see, for example, Bunn et al., "The Economics of Reprocessing vs. Direct Disposal of Nuclear Fuel", December 2003, pp. 98-101. With 50 percent in equity with a 6 percent real rate of return, 50 percent in bonds with a 3 percent real rate of return, a 25 percent corporate tax rate, and a 1 percent annual charge for insurance, the annual capital charge would be about 7 percent; for a simple 6 percent real rate with no taxes or insurance, the annual capital charge is 6.6 percent. (Both assume financing over 40 years.)

124 See, for example, the discussion in Bunn, Fetter, Holdren, and van der Zwaan, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel", pp. 98–101.

Table 5.2 shows per kilogram reprocessing costs for the high and low cost estimates for a 200 tHM/yr plant at these three levels of rate of return on capital. Table 5.3 shows the same results for an 800 tHM/yr plant.[125]

These tables include several factors not included in the capital and operating costs summary above:

- ***Interest During Construction (IDC)***. These are funds that have to be paid to lenders or investors while the facility is still under construction, and before it begins generating revenue. In effect, IDC adds to the total initial capital cost of the facility. For a ten-year typical construction time for a major reprocessing plant, IDC might add 19 percent to capital cost at a 3 percent rate of return, and 42 percent at a 6 percent rate of return.
- ***Decommissioning***. There is little experience actually decommissioning large commercial reprocessing plants, so figures available are largely based on estimates of what the cost will be in the future. The real costs of decommissioning nuclear facilities in both Britain and France are proving to be substantially higher than initially estimated, however, so these estimates should be taken with a grain of salt. For this study, decommissioning costs are assumed to be one quarter of facility capital costs, discounted for 60 years from the start of facility operations at a 3 percent rate. Because of the long period of discounting, the addition to reprocessing cost is modest; this approach adds less than 5 percent to the total capital cost for a decommissioning fund, a change much smaller than the uncertainties in these cost estimates.
- ***Capacity Factor***. Reprocessing plants, like other facilities, do not operate at full capacity throughout their lives. These tables assume that over their 40-year lives, the plants would operate, on average, at 80 percent of full capacity. This is higher than either the French or British reprocessing plants have achieved in practice.

As can be seen, there are large differences between the low-cost and high-cost estimates for the two types of plants, and between the 0 percent, 3 percent, and 6 percent financing scenarios. The per-kilogram cost of reprocessing ranges from $1,100 for the low-cost estimate for an 800 tHM/yr plant with zero financing costs (likely an unrealistic scenario) to over $5000 for the high-cost estimates at a 6 percent financing rate for both the 200 tHM/yr and the 800 tHM/yr plants. In the end, the cost is likely to be between these extremes.

125 In these tables, the capital costs are rounded to the nearest tenth of a billion dollars; the annual operating costs are rounded to the nearest $10 million per year; the capital and operating charges are rounded to the nearest $10 per kilogram; and the total reprocessing costs are rounded to the nearest $100 per kilogram.

It is worth noting that the cost per kilogram for 40 years of dry cask storage is in the range of $200/kgHM, between five and 25 times less than these estimated costs of reprocessing. Over the course of the 40-year life of the 800 tHM/yr reprocessing plant, with the low cost estimate and a 3 percent real financing rate, the difference would amount to over $30 billion. If those funds were not spent on reprocessing, they could be spent on providing as much as 10 GWe of additional nuclear power plants to provide clean electricity for China's economy. Of course, if the costs proved to be closer to the higher end of the range, the extra cost of reprocessing would be larger still.

Table 5.2: **Reprocessing Cost Per Kilogram, 200 tHM/yr Plant**

Plant	**Capital Cost**	**IDC**	**Decom.**	**Capital+ IDC+ Decom.**	**FCR**	**Capital Charge/ kg**	**Operating** (annual)	**Operating** (per kg)	**Total cost/ kg**
200 tHM/yr Low 0%	$3.2B	0	.04	$3.3B	0.025	$520	$190 M	$1,200	$1,700
200 tHM/yr Low 3%	$3.2B	0.19	.04	$4.0B	0.043	$1,070	$190 M	$1,200	$2,300
200 tHM/yr Low 6%	$3.2B	0.42	.04	$4.7B	0.066	$1,950	$190 M	$1,200	$3,100
200 tHM/yr High 0%	$5.7B	0	.04	$5.9B	0.025	$930	$340 M	$2,140	$3,100
200 tHM/yr High 3%	$5.7B	0.19	.04	$7.0B	0.043	$1,906	$340 M	$2,140	$4,000
200 tHM/yr High 6%	$5.7B	0.42	.04	$8.4B	0.066	$3,469	$340 M	$2,140	$5,600

Table 5.3: **Reprocessing Cost Per Kilogram, 800 tHM/yr Plant**

Plant	**Capital Cost**	**IDC**	**Decom.**	**Capital+ IDC+ Decom.**	**FCR**	**Capital Charge/ kg**	**Operating** (annual)	**Operating** (per kg)	**Total cost/ kg**
800 tHM/yr Low 0%	$8B	0	.04	$8.4B	0.025	$330	$480 M	$750	$1,100
800 tHM/yr Low 3%	$8B	0.19	.04	$9.9B	0.043	$670	$480 M	$750	$1,400
800 tHM/yr Low 6%	$8B	0.42	.04	$11.7B	0.066	$1,220	$480 M	$750	$2,000
800 tHM/yr High 0%	$20B	0	.04	$20.8B	0.025	$810	$1.5 B	$2,340	$3,200
800 tHM/yr High 3%	$20B	0.19	.04	$24.7B	0.043	$1,670	$1.5 B	$2,340	$4,000
800 tHM/yr High 6%	$20B	0.42	.04	$29.3B	0.066	$3,040	$1.5 B	$2,340	$5,400

All costs in 2014 dollars.

Box 5.1: **Estimating Interest During Construction**

The builder of a reprocessing plant needs money to build long before any reprocessing is done. Investors and lenders will typically want some return on their investment even while construction is still underway. This is known as interest during construction (IDC). How much IDC might increase the total cost of a facility depends on how long the facility takes to build before it begins providing the service it is built for; how spending is distributed over that time; and the rate of return. For different engineering projects, the distribution of spending over the construction period could be different. In general, investments during construction follow a typical S-curve (with slow spending at the beginning and end, and most spending concentrated in the middle years of construction), and that is what is assumed in the calculations in this report. Such an S-curve approach, however, may understate real IDC for a reprocessing plant. One of the largest costs is equipment procurement, and while the equipment might be installed in the middle or later stages of construction, it usually has to be ordered with a long lead time, in some cases before construction even begins.

China's pilot reprocessing plant is a good example of the uncertainties in estimating how long a project will take and what the schedule of spending during that time will be. Construction of the pilot plant started in 1998. Most of the construction was finished around 2002, but the plant was not fully completed until 2005. But it took another five years, until 2010, before it was actually commissioned (and then it operated for only ten days). If the construction period is considered as being from 1998 to 2005, then the investment distribution looks something like a typical S-curve. But if the construction period is considered to have lasted until 2010 or even 2015, the investment distribution would show an initial ramp up followed by a decade of very modest further investment. At a 3 percent rate of return, construction over 10 years with the typical S-curve distribution of spending used in this report would add 18-20 percent to the capital cost of the facility; at a 6 percent rate of return, the equivalent figure would be 41-43 percent. At the 3 percent rate, waiting another five years after the spend-out was largely complete before operations began would increase the IDC to 35-40 percent of the initial capital cost.

In practice, most Chinese nuclear projects have been delayed, as in the case of the pilot reprocessing plant and the CEFR. Construction of the AP-1000 at Sanmen began in 2009, and was initially slated to take four years. As of early 2015, it had been delayed to at least 2016, suggesting a seven-year construction time.[A] A Chinese nuclear expert stated at an IAEA meeting in 2014 that the Sanmen AP-1000 project was 20 percent over budget and at least two years behind schedule by the end of 2013, and the projected electricity price had increased from 6.7 U.S. cents to 8.3 U.S. cents. Only about one quarter of nuclear projects in China are completed within their initially projected budgets.[B] The delay would further increase the capital cost of the AP-1000 by adding to IDC. Similar delays should be considered likely in future reprocessing plants.

A Yap, Chuin-Wei and Brian Spegele, "China's First Advanced Nuclear Reactor Faces More Delays—Start-Up Now Unlikely Until 2016 at the Earliest," *The Wall Street Journal*, January 15, 2015. http://www.wsj.com/articles/chinas-first-advanced-nuclear-reactor-faces-more-delays-1421297393 (accessed January 4, 2016).

B Shan Sun, "Challenges during construction of new NPPS," at the IAEA Technical Meeting, February 4–7, 2014. http://www.iaea.org/NuclearPower/Downloadable/Meetings/2014/2014-02-04-02-07-TM-INIG/Presentations/37_S7_China_Sun.pdf (accessed January 4, 2016).

6. Potential Costs of Once-Through and Recycling Fuel Cycles in China

What would such costs of reprocessing mean for the overall cost of nuclear energy and its fuel cycle? That depends, of course, on the particular fuel cycles China decides to deploy. Moreover, making such estimates requires estimates of the other costs of the nuclear fuel cycle. For illustrative purposes, in this chapter we will use a $1400/kgHM estimate of the cost of reprocessing (the unit cost for the low cost estimate for an 800 tHM/yr reprocessing plant, with a 3 percent annual cost of money); a $200/kgHM estimate for the cost of 40 years of dry cask storage of spent fuel; an $1880/kgHM cost for MOX fuel fabrication (converting our $1500/kgHM 2003$ central estimate from an earlier report to 2014 dollars); and other fuel cycle costs as estimated in a comprehensive 2009 U.S. Department of Energy (DOE) report, updated to 2014 dollars.[126] While, except for the reprocessing cost estimates discussed in this report, these fuel cycle cost estimates were developed for the U.S. case, most are unlikely to be greatly different in China in the future. Table 6.1 shows the key estimates used in this chapter.

We have deliberately chosen cost estimates that are favorable to the case for reprocessing. The $1400/kgHM estimate for the cost of reprocessing is the lowest of any of the unit costs in the chapter above that include any financing cost at all. The cost of direct disposal from the DOE report is substantially higher than the 1 mill per kilowatt-hour fee the United States charges to utilities for spent fuel management (including transportation to the repository and disposal), which was repeatedly judged to be sufficient to finance the U.S. repository program when the Yucca Mountain repository was still planned, making the non-reprocessing route less competitive. The $200/kgHM dry storage cost is significantly higher than many recent estimates (roughly double the estimate in the DOE report). The

126 D.E. Shropshire, K.A. Williams, J.D. Smith, B.W. Dixon, M. Dunzik-Gougar, R.D. Adams, D. Gombert, J.T. Carter, E. Schneider, and D. Hebditch, *Advanced Fuel Cycle Cost Basis*, Rev. 2, INL/EXT-07-1207 (Idaho Falls: Idaho National Laboratory, December 2009). Conversion from 2009 to 2014 dollars using a multiplier of 1.0808, from U.S. Office of Management and Budget. For analysis leading to the 2003 estimate of $1500/kgHM for MOX cost, see Bunn, Fetter, Holdren, and van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, pp. 45-52. The much higher estimates for MOX fabrication cost in Shropshire et al. are based on (a) the very high costs of the U.S. MOX plant, and (b) private financing, which may not be appropriate for China. Shropshire et al. base their estimate of fabrication cost of MOX for fast breeder reactors on their LWR MOX fabrication cost estimate, with a cost increase of approximately 15 percent for the higher plutonium concentration and higher burnup of breeder core fuel; we have taken a similar approach, adding 15 percent to our lower MOX fabrication cost estimate, which may be more appropriate for government-financed facilities in China. Finally, Shropshire et al. estimate a cost for fabrication of fast reactor blanket fuel substantially higher than the cost of fabricating LEU fuel, but there seems little reason to expect that to be the case, so we have used a cost equal to the cost of fabricating LEU fuel.

MOX fabrication cost estimate may be appropriate for future facilities in China if design and construction proceed well and they are financed with government funds, but is just over half the estimate in the DOE report, much lower than estimated in a recent MIT study, and substantially lower than recent experience in the United States or Japan would suggest.[127] We assume that the direct disposal option encounters delays, so that all fuel going that route incurs the cost of dry cask storage as well as the cost of disposal. By contrast, on the reprocessing route we assume no substantial delays (despite the experience of all reprocessing programs to date), so that there is no cost assigned for long-term spent fuel storage before reprocessing; for plutonium storage between reprocessing and fuel fabrication; for separation of americium from the plutonium (typically necessary if the plutonium is stored long enough before use that gamma-emitting Am-241 builds up from decay of Pu-241); for substantial periods when the reprocessing plant or the MOX plant do not operate; or for long-term storage of HLW prior to disposal. Hence, the estimates in this chapter present an unrealistically favorable view of the likely economics of reprocessing in China.

Table 6.1: **Cost Estimates for Nuclear Fuel Cycle Elements**

Item	Nominal Cost Estimate (2014$)
Uranium ($/kgU)	$80
Conversion ($/kgU)	$10
Enrichment ($/SWU)	$120
LEU fabrication (PWR, $/kgHM)	$270
Reprocessing (LEU fuel, $/kgHM)	$1400
MOX fabrication ($/kgHM)	$1,880
Fast reactor MOX fabrication (core, $/kgHM)	$2170
Fast reactor fuel fabrication (blanket, $/kgHM)	$270
Dry storage (40 yr, $/kgHM)	$200
LEU spent fuel disposal ($/kgHM)	$700
HLW disposal ($/kgHM)	$280

127 The DOE study has a nominal cost estimate of $3,200/kgHM (2009 dollars), based on adjusting then-current estimates of the cost of the U.S. MOX plant for weapons plutonium disposition to reflect a somewhat different commercial facility (the cost of the U.S. MOX plant has continued to increase sharply since then, and the U.S. government is considering abandoning the project because of the hugely escalating costs). The MIT study gives a nominal cost estimate for MOX fabrication of $2,400/kgHM, with other figures similar to those in our table. Mujid Kazimi and Ernest J. Moniz, co-chairs, Charles W. Forsberg, study director, Steve Ansolobehere, John Deutch, Michael J. Driscoll, Michael W. Golay, Andrew C. Kadak, John E. Parsons, Monica Regalbuto, George Apostalakis, Pavel Hejzlar, and Eugene Schwaeraus, *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study* (Cambridge, MA.: MIT, 2011), p. 102. The not-yet-completed MOX plant in Japan is expected to have costs substantially higher than the $1,880/kgHM used in this study.

Consider, first, simply the relative costs of managing spent fuel by reprocessing it or by disposing of it, leaving out management of the resulting recovered plutonium and uranium (in effect, assuming that the value of these materials is equal to the cost of managing them, so that their net value is zero). The 2009 report estimates the cost of disposal of spent fuel at $650/kgHM ($700/kgHM in 2014 dollars), while it estimates that the cost of disposal of high-level waste (HLW) from reprocessing would be 2.5 times less, or $260/kgHM ($280/kgHM in 2014 dollars). Hence, if dry cask storage cost $200/kgHM, the cost of dry cask storage of spent fuel followed by disposal would be $900/kgHM. The cost of reprocessing plus disposal of the resulting wastes would be $1680/kgHM. In other words, reprocessing would almost double the cost of the back end of the nuclear fuel cycle.

Next, consider a complete fuel cycle cost estimate for a direct disposal fuel cycle versus one that reprocesses plutonium and recycles it as MOX in LWRs. Using a simple fuel cycle cost model from an earlier study, the total fuel cycle cost for a direct disposal fuel cycle with the individual unit costs in the table would be $2.46/MW-hr, while the cost for a reprocessing and MOX recycle fuel cycle would be two-thirds higher, at $4.16/MW-hr.[128] The price of uranium would have to rise to over $450/kgU before a closed fuel cycle with these prices would be economic. Because the fuel cycle is only a small part of the cost of nuclear energy, even a large change in fuel cycle cost represents only a modest change in total nuclear energy costs. But for a future 100 GWe fleet of nuclear reactors in China, it would mean an additional cost of over $1.2 billion per year.[129]

A recent MIT study on the future of the nuclear fuel cycle also concludes that shifting from a once-through cycle to a reprocessing and MOX use cycle would more than double the cost of the back-end of the nuclear fuel cycle.[130] The study argues that the lower cost of disposing of HLW compared to disposing of spent fuel "only appears to be a cost saving. Recycling the plutonium ultimately produces spent MOX fuel… which has an even higher disposal cost."[131] The study finds that the cost of fabricating plutonium into fuel and of disposing of spent MOX fuel is so high that the plutonium separated by reprocessing has a negative value of over $15,000 per kilogram.[132]

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128 For a description of the model, see Bunn, Fetter, Holdren, and van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Appendix A. The estimate in the text understates the cost of this closed fuel cycle option, because MOX spent fuel typically cannot be repeatedly recycled in LWRs, and is more expensive to store and dispose of, as it generates more heat; this additional cost is not included in this estimate.

129 A 100 GWe fleet operating at an 85 percent capacity factor would generate 745 million MW-hr per year. An excess cost of $1.69/MW-hr would lead to a total cost of over $1.2 billion.

130 Kazimi and Moniz et al., *The Future of the Nuclear Fuel Cycle*, p. 103.

131 Kazimi and Moniz et al., *The Future of the Nuclear Fuel Cycle*, p. 104.

132 Kazimi and Moniz et al., *The Future of the Nuclear Fuel Cycle*, p. 103.

Chinese analysts Zhou Chaoran, Liu Xuegang, Gu Zhongmao, and Wang Yugang have come to a strikingly different conclusion. They examined a once-through fuel cycle and a reprocessing and recycling MOX in LWRs fuel cycle for China, and concluded that "there is negligible [cost] difference between these two options."[133] There are several key drivers for their conclusion. First, they assume that reprocessing occurs 11 years after their base year, and MOX fabrication occurs 11.5 years afterward. Second, based on the MIT study, they choose a discount rate that is high for the government-financed Chinese nuclear market, 7.6 percent above the rate of inflation. In combination, these factors mean that the most important costs of the reprocessing fuel cycle are heavily discounted—cut by more than half just by their choice of timing for when these events occur, and their choice of discount rate. One of the key costs of the once-through fuel cycle, by contrast, uranium purchase, occurs five years before their base year, so with the high discount rate, its cost is increased by over 40 percent. They acknowledge that the costs of disposal of MOX fuel would be far higher than the costs of disposal of LEU fuel ($3130/kgHM for spent MOX disposal vs. $470/kgHM for spent LEU disposal, also taken from the MIT study), a factor not included in the model used here, but they discount the costs of MOX disposal more than 10 years farther into the future than they discount the costs of LEU disposal, to the point that the discounted cost of MOX disposal is less than 2.5 percent of its original, undiscounted cost.

Zhou et al. also use a $1,000/kgHM estimate of the cost of reprocessing, based on a previous Harvard study.[134] There are two major problems with this. First, the figure has not been updated to current dollars; in 2009 dollars (the year of the Zhou et al. study) it would be in the range of $1,160, and in 2014$ (relevant for this study) it would be $1250. More important, the $1,000/kgHM figure, as described in the original Harvard study, is *only* attainable at realistic capital and operating costs if financing costs are ignored (as discussed above).[135] As the original study pointed out, with government financing over a 30-year facility lifetime, the per-kilogram cost for a facility with the capital and operating costs estimated for THORP would be $1,350/kgHM ($1690/kgHM in 2014 dollars). For a privately financed facility with a regulated, low-risk rate of return (comparable to the

133 Chaoran Zhou, Xuegang Liu, Zhongmao Gu, and Yugang Wang, " Economic Analysis of Two Nuclear Fuel Cycle Options," *Annals of Nuclear Energy*, Vol. 71 (2014), pp. 230–236.

134 Zhou et al., "Economic Analysis," p. 232, citing Bunn, Fetter, Holdren, and van der Zwaan.

135 Bunn, Fetter, Holdren, and van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*. On p. ix, the study notes that the $1000/kgHM figure is "substantially below the cost that would pertain in privately financed facilities with identical costs and capacities to the commercial facilities now in operation." The costs for government-financed facilities and those financed by regulated and unregulated private entities are discussed on pp. 31-34. The DOE study also suggests a nominal cost of reprocessing in the $900-$1,300/kgHM range, which is also based on the unrealistic scenario of zero financing cost. See Shropshire et al., *Advanced Fuel Cycle Cost Basis*, p. F1-15 (showing calculations that exclude any financing cost) and p. F1-16 (showing the resulting estimates).

discount rate in the Zhou et al. study), the cost of reprocessing at the same plant would be over $2000/kgHM (over $2500/kgHM in 2014$). Hence, Zhou et al.'s use of the $1,000/kgHM figure in a market with a 7.6 percent real cost of money is simply incorrect.

It is also important to understand that the rate of return required to attract investors or lenders to finance a risky project and the rate of return that should be assumed to be available on money set aside in risk-free investments to cover future obligations such as disposal or decommissioning are not the same rate. It is simply incorrect to use a discount rate like 7.6 percent for the risk-free rate at which to discount future disposal or decommissioning costs.

Moreover, as the fuel cycle is likely to be government-financed in China in any case, a 3 percent real rate, as used in this study, is likely to be much closer to reality than the 7.6 percent real rate used in the Zhou et al. study. If, in fact, one adopts a 3 percent real rate; moves reprocessing to 5 years after fuel discharge; moves MOX fabrication to occur before fuel loading, for a fair comparison with LEU fuel fabrication; and puts the other Zhou et al. cost figures into the model from the earlier Harvard study (without the extra cost for MOX disposal, not included in that model), one finds that the fuel cycle cost for reprocessing is over 70 percent higher than the fuel cycle cost for direct disposal, consistent with the findings in this study.

China, in any case, does not plan to recycle plutonium in LWRs, but in fast-neutron breeder reactors (FBRs) to be built in the future. For a fuel cycle involving different reactors, the cost of the reactors themselves—the dominant part of the cost of electricity from nuclear energy—must also be considered. These costs are uncertain, as the specific FBRs China might build for commercial deployment have not yet been designed.

Traditionally, FBRs have been substantially more expensive per kilowatt of installed capacity than LWRs.[136] While FBR designers are working to develop cheaper systems and hope someday to be able to match or beat the cost of LWRs, designers of LWRs and other thermal reactors are also seeking to lower costs, and most analysts believe that the capital cost of future FBRs will be in the range of 20–50 percent more than the cost of LWRs of a similar design level.[137] This is certainly true of the Russian BN-800 fast reactors China has considered purchasing. Russia's nuclear industry, like China's, is focused on closing the fuel cycle, but as the first BN-800 was

136 For a critical review of the history and results of FBR programs around the world, see Thomas B. Cochran, Harold A. Feiveson, Walt Patterson, Gennadi Pshakin, M.V. Ramana, Mycle Schneider, Tatsujiro Suzuki, and Frank von Hippel, Fast Breeder Reactor Programs: History and Status (Princeton, N.J.: International Panel on Fissile Materials, 2010), http://fissilematerials.org/library/rr08.pdf (accessed January 5, 2016) For cost estimates for real and proposed FBRs, see Shropshire et al., *Advanced Fuel Cycle Cost Basis*, Module R2.

137 See, for example, Shropshire et al., Advanced Fuel Cycle Cost Basis, Module R2, and Kazimi and Moniz et al., *The Future of the Nuclear Fuel Cycle*, p. 23 and p. 27.

being built, Minister of Atomic Energy Alexander Rumiantsev acknowledged that "life has proved that a VVER-1000 reactor [then the current Russian LWR design] is one and a half times cheaper than a BN [FBR] reactor… [LWRs] are cheaper, safer, and economically more viable."[138] In 2015, Russia decided to postpone its follow-on BN-1200 design in an effort to reduce its excessive costs.[139]

Consider the effect on nuclear energy costs if, in the future, China is able to build LWRs at a cost of $3,000/kW of installed capacity, and the cost of FBRs is 20 percent higher ($3,600/kW). Assuming that these reactors could each be built in four years, with financing at a 3 percent real rate, and that they would be financed over 40 years with an 85 percent capacity factor, the levelized cost of electricity from the once-through LWR (again, using the simple model from a previous Harvard study) would be $0.041/kW-hr, while the levelized cost of electricity from the fast reactors fueled by recycling plutonium would be $0.049/kW-hr, roughly 20 percent higher.[140] (The electricity costs are so low because of the very low financing cost compared to private financing in the United States or Europe, and the low capital cost compared to those being experienced in the United States and Europe.) This difference is not a surprise, as the capital cost is 20 percent higher, and the capital cost dominates the cost of the nuclear energy. The fuel cycle cost for the FBRs is much higher, but contributes only a small part of the total cost, and operations and maintenance costs are also projected to be somewhat higher.[141] The cost of uranium would again have to increase to over $450/kgU before FBRs at these costs would be economically justified. In some versions of this fuel cycle, the eventual nuclear fleet would be a mix of LWRs and fast reactors, potentially diluting the difference in electricity price. Nevertheless, it is clear that unless the capital cost of FBRs can be reduced to equal that of LWRs, going this route would make nuclear energy significantly less economically competitive for decades to come.

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138 Sergey Savenkov, "Minister Rumiantsev: Minatom Will Not be Privatized," (interview), www.uralpress.ru, April 4, 2003 (translated by U.S. Department of Energy).

139 "Russia Postpones BN-1200 in Order to Improve Fuel Design," *World Nuclear News*, April 16, 2015, http://www.world-nuclear-news.org/NN-Russia-postpones-BN-1200-in-order-to-improve-fuel-design-16041502.html (accessed January 4, 2016).

140 For a description of the model, see Bunn, Fetter, Holdren, and van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, App. A. For the overall electricity costs, in this study we have also taken operations and maintenance (O+M) costs for the two types of reactors from Shropshire et al., *Advanced Fuel Cycle Cost Basis*, Modules R1 and R2. They divide O+M costs for future reactors into a fixed component and a variable component. For LWRs, the fixed component is $66/kWe-yr ($71 in 2014$), while the variable component amounts to $1.8/MW-hr ($1.9 in 2014$). See p. R1-14. For fast reactors, they project O+M costs of $70/kWe-yr ($76 in 2014$) and $2/MW-hr ($2.2 in 2014$). The fast reactor O+M costs are 8-11 percent higher than those of LWRs.

141 See Shropshire et al., Advanced Fuel Cycle Cost Basis, Module R2. See also Kazimi and Moniz et al., *The Future of the Nuclear Fuel Cycle*, p. 106. The MIT study ultimately finds a much lower increment to electricity cost from the use of fast reactors, in part because the study balances the extra capital cost of the fast reactors with a large payment for taking the transuranics generated by reprocessing.

7. The Right Reprocessing Approach? China's Potential for Leapfrogging

Beyond economics, another question is whether the proposed 200 tHM/yr or 800 tHM/yr plants are the best reprocessing facilities for supporting either China's near-term fuel cycle programs or China's longer-term fuel cycle goals. It is not obvious that they are.

7.1 Supporting China's Near-Term Fuel Cycle Plans

As currently envisioned, the main role of the proposed reprocessing facilities would be to support the demonstration and eventual commercial FBRs that China hopes to build. The reprocessing plants would provide plutonium for starting up the FBRs.

But it is not clear that reprocessing plants are needed for this purpose, for two reasons. First, reprocessing countries have already built up stocks of over 260 tons of unused separated civilian plutonium. They would be happy to provide start-up plutonium to China for a price dramatically smaller than the price of building and operating reprocessing plants.

Second, as the MIT fuel cycle study pointed out, fast reactors can be started up with enriched uranium, rather than plutonium, as China has done with the CEFR. As the MIT study notes:[142]

> The use of enriched uranium to start fast reactors with near unity conversion ratio provides a scheme to divorce the speed with which fast reactors can be deployed from the availability of TRU [transuranics] to fuel their initial cores. This facilitates a faster penetration of the nuclear energy system by fast reactors. The lower conversion ratio compared with breeders may also permit a greater range of FR technologies. In addition, such a route to fast reactors avoids the building of a large thermal fuel recycling capacity, which is the costly part of nuclear fuel recycling infrastructure.

By either of these means, China could skip the large expense of building and operating reprocessing plants for light-water-reactor fuel—the "costly part" of nuclear fuel recycling.

142 Kazimi and Moniz et al., *The Future of the Nuclear Fuel Cycle*, p. 97.

Even if China prefers to build reprocessing plants to provide start-up plutonium, the 200 tHM/yr plant, which, if it operates well, might provide up to two tons of separated plutonium per year, would easily provide sufficient start-up plutonium for the proposed 600 MWe demonstration reactor and the proposed 1000 MWe commercial reactor. An 800 tHM/yr plant for reprocessing LWR fuel would not be needed unless China was planning to launch a large number of breeders quickly, above and beyond those that could be fueled with the plutonium produced in the breeder reactors.

Moreover, the currently proposed reprocessing plants would not allow China to demonstrate the full potential of a closed nuclear fuel cycle, which requires reprocessing the FBR spent fuel and fabricating new plutonium fuel for the FBRs. Reprocessing FBR fuel is quite different from reprocessing LEU LWR fuel, because of the much higher concentrations of plutonium in FBR core fuel (which makes it more difficult to dissolve and requires equipment designed to avoid criticality when these higher plutonium concentrations are dissolved). Moreover, for the longer term, China may switch to nitride, carbide, or metal fuels for future FBRs, rather than oxide fuels; those other fuel chemistries would require very different approaches to reprocessing. Yet both the planned 200 tHM/yr plant and the proposed 800 tHM/yr plant are mainly designed to reprocess LWR fuel, and the French proposal for the 800 tHM/yr facility is integrated with MOX fabrication, where France's only substantial experience is in producing LWR MOX. China might conclude that a better option would be to wait and develop technologies designed for reprocessing and fabricating FBR fuel.

7.2 Supporting China's Long-Term Fuel Cycle Ambitions

In the long term, China hopes to be a world leader in all aspects of nuclear energy technology, including the nuclear fuel cycle. Building a 200 tHM/yr plant based on scaling up a pilot plant that has so far been largely unsuccessful, and is based on PUREX technology that dates to the 1940s and has a wide range of well-understood problems would not be likely to put China in a leadership position. Such a plant would be much more a facility for gaining more experience with existing technology than a facility for developing new approaches. Similarly, buying an 800 tHM/yr reprocessing plant from France would give China access to leading French technologies—but these are still based on aqueous technology for processing LWR fuel, an approach that has proved to raise significant cost, safety, and security issues.

Meanwhile, a number of countries are exploring new concepts for management and processing of spent fuel. The United States has been exploring a family of aqueous processes known as UREX+, along with R&D to demonstrate the safety of dry cask storage and direct disposal with high-burnup fuels. Russia is planning to build a commercial reprocessing plant not based on aqueous technology at all, but on electrometallurgical processing. South Korea, similarly, is exploring pyroprocessing, in cooperation with the United States. India is exploring future fuel cycles involving carbides or nitrides, and the reprocessing technologies that might be needed for them.

To establish a leadership position, an alternative approach would be for China to build an R&D facility that would allow it to explore a variety of approaches to management of different types of spent fuel, to develop new concepts that might resolve some of the problems reprocessing has faced in the past. A flexible R&D facility, pursuing an appropriate research agenda, could help China leapfrog other countries in spent fuel management technology, rather than simply replicating what China or other countries have done in the past.

At the same time, China could continue to accumulate funds paid by reactor operators for spent fuel management, so that money would be available in the future to implement whatever spent fuel management option China ultimately chooses. This would allow time for technology to develop, interest on the funds to accumulate, and economic, technological, and political circumstances to clarify, without foreclosing any options. The funds not spent on near-term construction of reprocessing plants could be used to build additional nuclear reactors, providing more electricity for China.

7.3 Non-Economic Costs to Be Considered

The costs of building large reprocessing plants in the near term would not only be economic. Designing, building, and operating such facilities will require large numbers of highly qualified experts and workers. All of these people will have to be recruited and trained, at a time when providing qualified personnel to support the rapid growth of nuclear energy in China is posing major challenges. Chinese nuclear regulatory agencies face particular challenges, and would have to acquire a wide range of expertise in areas quite different from those needed for nuclear reactor regulation to effectively regulate large reprocessing and plutonium fuel fabrication facilities. Overall, an investment in large reprocessing facilities would tend to divert both money and skilled personnel away from safe and secure construction and operation of nuclear reactors.

8. Conclusions and Recommendations

As China expands its civil nuclear energy program, it faces a major decision: whether to make large investments in commercial-scale reprocessing plants and fast-neutron breeder reactors in the near term, or whether to wait, allocate those resources to R&D and other projects for the time being, and allow more time for technology to develop, interest to accumulate on funds set aside for spent fuel management, and political, economic, security, and technical circumstances to clarify.

Fortunately, China has the luxury of time. China has access to sufficient uranium to fuel even aggressive nuclear energy growth for decades to come.[143] The technology of dry cask storage makes it possible to store spent nuclear fuel cheaply, safely, and securely for decades, leaving all options for the future. Overall, we believe that postponing major investments in reprocessing and breeder reactors would best serve China's interests. Resources not devoted to reprocessing in the near term could be spent on additional nuclear reactors, offering more clean energy for China's economy. China can also establish a flexible R&D facility, pursuing a wide range of technologies and approaches for managing spent fuel, potentially allowing China in the future to leapfrog the technologies used in other countries, rather than copying old technologies.

China's future fuel cycle needs are uncertain. For example, if uranium continues to be cheap and plentiful for decades to come, as most analysts expect, China will have little need for plutonium recycling to fuel its nuclear energy needs. Similarly, if China's efforts focused on high-temperature pebble-bed reactors (PBRs) or its earlier-stage investments in fluoride salt-cooled high-temperature reactors (FHRs) result in attractive reactor systems for the future, fuel cycle concepts for reprocessing and breeder reactors may have a reduced role. Further, events from climate disasters to additional nuclear accidents or terrorist incidents could affect thinking about the desirability of large-scale nuclear energy growth, which in turn could affect whether and when China might find it desirable to close the nuclear fuel cycle. This uncertainty highlights the desirability of China pursuing approaches that leave future options open, and avoid expensive lock-in to particular pathways today.

143 Hui Zhang and Yunsheng Bai, *China's Access to Uranium Resources.* Cambridge, MA: Report for Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, May 26, 2015.

This report has made clear that building large reprocessing plants in the near term would be expensive, with initial capital costs likely in the range of $3.2–$5.7 billion 2014 dollars for the 200 tHM/yr plant, or $9 billion to over $20 billion 2014 dollars for the 800 tHM/yr plant. Life-cycle costs for these facilities would amount to tens of billions of dollars, far more than the cost of storing the fuel. Even with favorable assumptions for reprocessing, the analysis in this report suggests that shifting to a reprocessing and recycling fuel cycle in light-water reactors (LWRs) would increase the cost of the nuclear fuel cycle by two-thirds (though the effect on the total cost of nuclear energy would be modest). A fuel cycle based on fast-neutron breeder reactors could increase total nuclear energy costs by 20–50 percent, because of the expected higher capital, operating, and fuel cycle costs of breeder reactors than once-through LWRs.

We recommend that China take the following steps:

- Undertake a comprehensive review of the economic, safety, security, nonproliferation, and waste-management benefits and risks of near-term construction of reprocessing plants and breeder reactors versus those of continuing to store spent nuclear fuel for several decades. Ultimately, China should choose the option that brings the best balance of costs, risks, and benefits.
- Invest in both at-reactor and centralized dry cask storage facilities, which offer important flexibility for any fuel cycle option chosen.
- Set aside funds for spent fuel management in risk-free accounts, ensuring that funds will be available in the future to implement whatever spent fuel management approaches are ultimately chosen.
- Approve major reprocessing and breeder reactor projects only if they would still be worthwhile if the cost were two-to-three times higher than the early estimates (and the schedules substantially longer), taking into account that early cost estimates are likely to grow.
- Avoid technological and institutional lock-in on one approach to the extent practicable, maintaining flexibility to adapt to future developments.
- Pursue R&D on fuel-cycle technologies, intended to put China in a leadership role in these technologies.
- Ensure that the potential nuclear proliferation impacts of China's choices—and in particular how China's choices may affect the spread of reprocessing technologies in non-nuclear-weapon states—are fully considered in choosing the best option for China.

- Ensure that the chosen approach is implemented in a way that meets the highest standards of safety, security, safeguards, and waste management. In particular:
    - Ensure that Chinese regulatory agencies have the resources, expertise, authority, and culture needed to provide effective oversight of both safety and security.
    - Avoid storing high-level wastes as liquids for extended periods, or storing spent nuclear fuels in densely packed pools that could lead, if drained, to fuel overheating or a spent fuel fire.
    - Work to build support for facility siting in local communities, involving them in decisions, and adopting the basic principle that facilities will not be built in communities that do not want them.
    - Avoid building up stockpiles of civilian separated plutonium beyond those needed for immediate use.
    - Ensure that facilities and transports will be safe in the face of a wide range of potential internal and external events.
    - Ensure that facilities and transports will be secure in the face of a wide range of potential adversary capabilities and tactics.[144]
    - Design in effective safety, security, and safeguards from the outset, achieving better safety and security at lower cost. In particular, design any reprocessing or plutonium fuel fabrication plants to be capable of accepting IAEA safeguards, to be able to meet the requirements of the U.S.-China 123 agreement, and the potential future requirements of a fissile material cutoff or other agreements limiting plutonium production.

China has the world's largest nuclear construction program, and within a couple of decades, China is likely to have the largest number of nuclear power plants in the world. China is already becoming one of the world leaders in nuclear energy technology, and has every reason to seek to maintain and strengthen that leadership role. Pursuing the safest, most secure, and most cost-effective approaches available today—while pursuing a vigorous R&D program on new approaches for the future—is likely to be the best way to promote China's nuclear energy leadership.

144 Hui Zhang and Tuosheng Zhang, *Securing China's Nuclear Future.* Cambridge, MA: Report for Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, March 14, 2014.

Appendix 1: The Effect of Currency Exchange Rates and Inflation

Substantial uncertainties arise from both comparing construction projects across different national environments and comparing them between different historical periods. These uncertainties arise both from difficulties in estimating the real value of different currencies against each other and from different rates of inflation for different types of activity in different countries.

Uncertainties in converting currencies

Simply converting a cost estimate in one currency into another currency at market exchange rates may not accurately reflect how the construction costs would differ from one country to another. A bowl of noodles costs much less in China than one would expect from simply taking the cost of a similar bowl in the United States and converting it to Chinese currency at market exchange rates. To partly resolve such issues, the World Bank and others have developed estimates of exchange rates adjusted for purchasing power parity (PPP) for each year for major economies. There are significant controversies and uncertainties over this procedure, however, particularly as the relative costs of particular items may vary in different countries. In some countries, labor is cheap but technology is expensive, while in others the reverse might be true. A detailed comparison of costs of particular facilities between such countries would require a breakdown of the item-by-item costs of the facility that is well beyond the scope of this paper.

Simply using PPP exchange rates also does not always reflect the full picture. For a construction project in which almost all of the inputs (labor, materials, components, and the like) are being sourced from within a country's own economy (such as the construction of China's pilot reprocessing plant), use of a PPP exchange rate is appropriate for expressing the cost in other currencies (such as dollars). For a project where a large fraction of the cost is spent on international markets (as might be the case if China purchased a commercial reprocessing plant from France), use of market exchange rates is more appropriate.

For the purposes of this paper, we will generally use a conversion based on PPP exchange rates in the year the cost was estimated or the money was spent, whichever is available.[145] In cases of especially large and important costs (such as the capital costs of major reprocessing facilities), we also report costs based on market exchange rates (using a three-year average of the exchange centered on the year of the estimate or the year the money was spent, to smooth out currency fluctuations).

Uncertainties resulting from differing rates of inflation

In estimating future costs based on costs of analogous plants built in the past, there are also issues in what inflation rate to assume. Estimates of the general inflation rate for most major economies are available from a variety of sources. Construction costs in many countries are rising faster than the rate of inflation, however.

In the United States, for example, according to a widely used construction cost index prepared for many years by the *Engineering News Record,* average construction costs were 55 percent higher in 2014 than they had been in 2000.[146] In the wider U.S. economy, prices had only increased 32 percent during that period.[147]

Prices for major energy facilities have been rising at a still higher rate, and nuclear construction costs have been rising faster than that—to the point that some companies producing power plant construction cost indices also produce another version of their index without nuclear power to avoid distorting the overall rate of price increases in the industry.

Figure Appendix 1.1 shows the situation for power plants in North America; the situation for Europe is similar.[148] On average, on the portion of the index including nuclear plants, power plants were 2.29 times as expensive in 2014 as they were in 2000; non-nuclear power plants were 1.87 times as expensive. Hence, if this study used construction cost indices rather than general inflation figures, the estimated present-day cost of the reprocessing plants described would be substantially higher.

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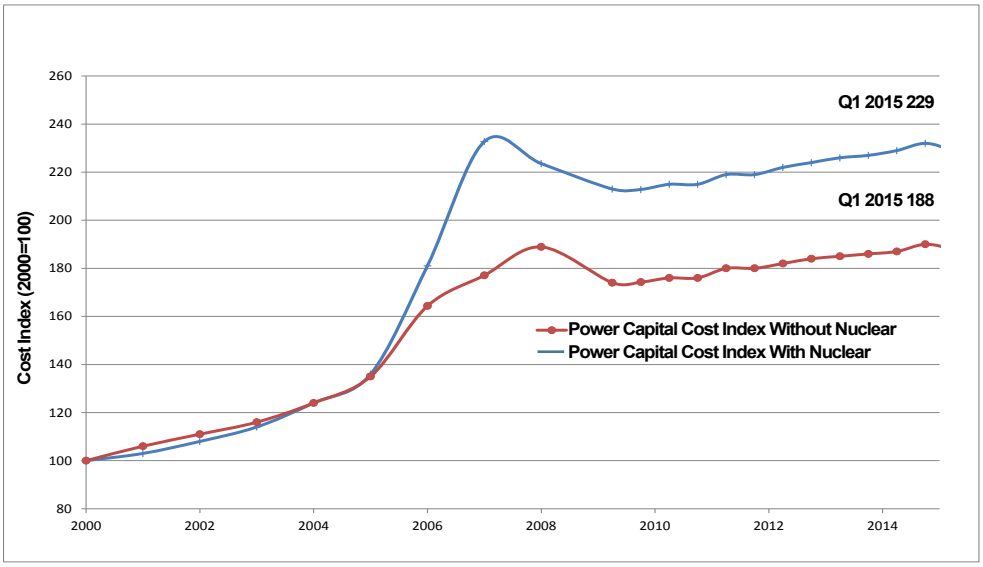
145 PPP figures are from Organization for Economic Cooperation and Development, "OECD Stat, National Accounts," Section 4, "PPP and Exchange Rates," https://stats.oecd.org/Index.aspx?DataSetCode=SNA_TABLE4 (accessed September 12, 2015).

146 "Engineering News Record Construction Cost Index History," http://enr.construction.com/economics/historical_indices/construction_cost_index_history.asp (accessed March 6, 2015).

147 U.S. Office of Management and Budget, "Historical Tables: Gross Domestic Product and Deflators Used in the Historical Tables, 1940-2020" (Washington, D.C.: OMB, 2015), http://www.whitehouse.gov/omb/budget/Historicals (accessed March 13, 2015).

148 IHS Cambridge Energy Research Associates (IHS-CERA), "IHS CERA Power Capital Cost Index" (Cambridge, MA: IHS CERA, 2014), https://www.ihs.com/info/cera/ihsindexes/Index.html (accessed March 10, 2015).

Figure Appendix 1.1: **Quickly Rising Power Plant Prices, Especially Nuclear**



It might be objected that a reprocessing plant is not a nuclear power plant, and construction cost inflation in China in general, and nuclear construction cost in particular, may not be as high. Indeed, the increase in price in 2000–2012 in what the Chinese statistics agency calls "Construction and Installation" was slightly lower than the price increase for the Chinese economy as a whole, reflected in World Bank GDP deflators (54 percent versus 68 percent).[149]

On the other hand, a "geographically diversified" index of construction cost of downstream chemical facilities, including facilities in Asia and elsewhere, shows a pattern similar to that for the North American power plants, with an overall 98 percent increase in facility cost from 2000 to 2012 (the most recent year for which data were available).[150] This compares to general inflation over that period in the United States of 28 percent, and in China of 68 percent.

Nevertheless, for the purposes of this study, we will convert currencies into dollars at the year of the estimate (or the year in which the money was spent) and inflate to the present using the general inflation rate for the U.S. GDP. This likely understates the likely future cost of reprocessing plants.

149 Calculations based on data from *China Statistical Yearbook* 2013 (Beijing: China Statistics Press, 2014), http://www.stats.gov.cn/tjsj/ndsj/2013/indexeh.htm (accessed March 13, 2015), and World Bank, "GDP Deflator (Annual %)," http://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG (accessed March 13, 2015).

150 IHS CERA, "Downstream Capital Costs Index" (Cambridge, MA: IHS CERA, 2012), https://www.ihs.com/info/cera/ihsindexes/Index.html (accessed January 4, 2016).

Appendix 2: Recent international projections of reprocessing costs

Given the growth in costs that typically occurs in moving from projections to real plants, the real cost experience at real plants is the best predictor of the costs of future plants. Nevertheless, it is worth briefly examining some recent projections of reprocessing costs.

Harvard University, 2003. In 2003, a Harvard group published *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel.*[151] That report examined key costs of both reprocessing and direct disposal fuel cycles, and concluded that even with assumptions favorable to the reprocessing option, reprocessing with then-projected prices would increase the cost of the back end of the nuclear fuel cycle by some 80 percent. Reprocessing would not be economic until the price of uranium reached $360 per kilogram of uranium (kgU). To be conservative, the report used a cost of reprocessing of $1000 per kilogram of heavy metal in spent fuel (kgHM)—$1,250/kgHM in 2014 dollars—while noting that this was "substantially below the cost that would pertain in privately financed facilities with identical costs and capacities to the large commercial facilities now in operation."[152]

Massachusetts Institute of Technology (MIT), 2003 and 2011. In 2003, an MIT group published *The Future of Nuclear Power,* which explored a broad range of issues surrounding potential large-scale nuclear energy growth, including management of the back end of the nuclear fuel cycle.[153] Consistent with a Harvard study the same year, the study concluded that reprocessing would be far more expensive than direct disposal.[154] The authors estimated that 5.26 kilograms of LEU spent fuel would have to be reprocessed to recover enough plutonium for one kilogram of LWR MOX fuel. With the cost of reprocessing estimated at $1000 for each of the 5.26 kilograms of LEU spent fuel (and $300 per kilogram for disposal of the resulting HLW), and an estimated $1500 MOX fabrication cost, the total cost for one kilogram of MOX was over $6600 (even after subtracting the value of the

151 Matthew Bunn, Steve Fetter, John P. Holdren, and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Cambridge, MA: Project on Managing the Atom, Harvard University, December 2003), http://belfercenter.hks.harvard.edu/files/repro-report.pdf (accessed March 5, 2015).

152 Bunn, Fetter, Holdren, and van der Zwaan, *The Economics of Reprocessing*, p. ix.

153 John Deutch and Ernest J. Moniz, co-chairs, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, MA: Massachusetts Institute of Technology, 2003), http://web.mit.edu/nuclearpower/ (accessed March 5, 2015).

154 Matthew Bunn, Steve Fetter, John P. Holdren, and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Cambridge, MA: Project on Managing the Atom, Harvard University, December 2003), http://belfercenter.hks.harvard.edu/files/repro-report.pdf (accessed March 5, 2015).

uranium recovered by reprocessing), while the cost of a kilogram of LEU fuel of equivalent energy value was estimated at just under $1690, almost four times less.[155] The study did not describe capital and operating costs for reprocessing plants to justify its $1000/kgHM estimate for reprocessing or its $1500/kgHM for MOX fabrication. These figures were in 2002 dollars; in 2014 dollars, they would come to $1270/kgHM and $1910/kgHM respectively. The study strongly recommended that the United States continue on a once-through fuel cycle, and argued that R&D should focus primarily on once-through options.

In 2011, a similar MIT team published a follow-up report, *The Future of the Nuclear Fuel Cycle*.[156] The study again concluded that the costs of recycling were higher than the costs of direct disposal. In this case, the study estimated the cost of reprocessing at $1600/kgHM (2007$), and the cost of MOX fabrication as $2,400/kgHM.[157] Once again, there was not an analysis of the capital and operating costs of facilities that would lead to these per-kilogram costs. In 2014 dollars, these figures would be $1,790/kgHM and $2,680/kgHM, respectively. The study noted that reprocessing of fast reactor fuel, with its much higher fissile content, would be much more expensive (estimated at $3,200/kgHM, 2007$), and estimated that both the capital costs and the non-fuel operating costs of fast reactors would be 20 percent higher than those of LWRs.[158]

Importantly, the group concluded that there was sufficient uranium in the world to power nuclear energy growth for an extended period, and that reactors with high breeding ratios "are not required for sustainable closed fuel cycles that enable full utilization of uranium and thorium resources." Hence it would be possible, even if recycling was someday needed, to use a wider range of alternatives, including "startup of fast reactors with low-enriched uranium rather than high-enriched uranium or plutonium, thereby eliminating the need for reprocessing LWR SNF [spent nuclear fuel] for closed fuel cycle startup."[159] The group again recommended that the United States stick with an open fuel cycle for decades to come, at least, and suggested that all fuel cycles should be designed to include flexible spent fuel storage for periods of up to a century.

155 *The Future of Nuclear Power*, pp. 146-147. These are the figures not including carrying charges. With carrying charges, the totals were estimated at $2,040/kgHM for LEU and $8,890/kgHM for MOX.

156 Mujid Kazimi and Ernest Moniz, co-chairs, *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study* (Cambridge, MA: MIT, 2011), http://mitei.mit.edu/system/files/The_Nuclear_Fuel_Cycle-all.pdf (accessed March 5, 2015).

157 *The Future of the Nuclear Fuel Cycle*, p. 102.

158 *The Future of the Nuclear Fuel Cycle*, p. 102.

159 *The Future of the Nuclear Fuel Cycle*, p. xii.

Boston Consulting Group, 2006. In 2006, the Boston Consulting Group (BCG) published a study sponsored by the French nuclear firm AREVA, which argued that, contrary to the MIT and Harvard studies, the costs of reprocessing and direct disposal in the United States would be roughly similar.[160] BCG achieved this result by assuming that:

- The French reprocessing facilities could be scaled up to a substantially larger size at little additional capital cost;
- A new plant would have reduced costs compared to the existing French plants because certain facilities could be eliminated and the duplication of having two plants could be avoided;
- MOX fabrication would be integrated into the reprocessing plant at little additional capital or operating cost;
- The plant would be financed by the U.S. government at a government cost of money;
- Disposing of HLW would cost far less than disposal of LEU spent fuel, and no extra cost would need to be paid for disposal of spent MOX fuel, despite its much higher heat content than LEU spent fuel; and
- The combined reprocessing and MOX fabrication plant would operate at full capacity throughout its life, without delays or interruptions (something no reprocessing plant in history has ever achieved).

Overall, BCG estimated that a 2,500 tHM/yr reprocessing plant (far larger than any such facility in the world) with integrated MOX fabrication (which has never been done before) could be built in the United States by 2020 for an overnight capital cost of $16 billion (2005$), with an annual operating cost of $890 million.[161] With the low financing cost, this resulted in a combined cost for reprocessing and MOX fabrication of $630/kgHM—far lower than real plants had achieved for either process alone. Real plants built in the future are highly unlikely to match these BCG cost estimates.[162] In particular, AREVA, BCG's client, has never actually offered to build a plant at anything resembling this price (as noted earlier in this report, AREVA has proposed a substantially higher price for a plant of one-third this capacity in China).

160 Boston Consulting Group, *Economic Assessment of Used Nuclear Fuel Management in the United States* (Boston: BCG, July 2006), https://www.bcg.com/documents/file15203.pdf (accessed March 5, 2015).

161 BCG, *Economic Assessment of Used Nuclear Fuel Management*, p. 16.

162 For a critique of the BCG report, see Matthew Bunn, "Assessing the Benefits, Costs, and Risks of Near-Term Reprocessing and Alternatives," testimony before the Subcommittee on Energy and Water, Committee on Appropriations, U.S. Senate, September 14, 2006, http://belfercenter.hks.harvard.edu/files/bunn_gnep_testimony.pdf (accessed March 5, 2015).

U.S. Advanced Fuel Cycle Initiative, 2009. The U.S. Advanced Fuel Cycle Initiative has been doing detailed estimates of various characteristics of different fuel cycles, including costs, for years, with the participation of a range of U.S. experts, primarily from the U.S. national laboratories. The comprehensive AFCI report on fuel cycle costs that was most recent as of mid-2015 was published in 2009.[163] The study provides a useful table of the costs of past reprocessing plants (with more plants included but less official and up-to-date data than in the present study).[164] The study estimates that a "benchmark" 800 tHM/yr plant would have a capital cost of $10.2–$14.2 billion, and an annual operating cost of $254–$377 million (2007$).[165] This capital cost is similar to those reported for THORP and UP2-800/UP3, described above, but the estimated operating cost appears unrealistically low compared to those reported for those facilities. The study argues that the exponent for scaling from modest reprocessing plants to larger ones may be substantially lower than the 0.9 used in the Chinese estimates in this paper.[166] Assuming no financing costs at all and operation at full capacity for 40 years, the study estimates the unit cost of reprocessing in a range between $1,108-$1,619/kgHM, with a central estimate of $1,370/kgHM (2009$).[167] More complex aqueous processing such as the UREX+ family of processes would be substantially more expensive. Although advocates of pyroprocessing sometimes argue that it would be substantially cheaper than aqueous processing, the AFCI study concluded that pyroprocessing of fast reactor fuel, integrated with fuel fabrication from the products, would cost $3,000-$9,000/kgHM, with a central estimate of $6,000/kgHM (2009$).[168] The study estimated the cost of LWR MOX fabrication at $3,000-$5,000/kgHM, with a central estimate of $3,200/kgHM (2009$).[169]

Nuclear Energy Agency, 2013. In 2013, the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) returned to the topic of the economics of the fuel cycle in a major report.[170] The report found that a once-through fuel cycle was cheaper than limited recycling as MOX in LWRs or repeated recycling in LWRs and fast reactors.[171] The study estimated the cost of an integrated reprocessing and MOX

163 Shropshire et al., *Advanced Fuel Cycle Cost Basis*.

164 Shropshire et al., *Advanced Fuel Cycle Cost Basis*, p. F1-14.

165 Shropshire et al., *Advanced Fuel Cycle Cost Basis*, pp. F1-14-15.

166 Shropshire et al., *Advanced Fuel Cycle Cost Basis*, pp. F1-8-10.

167 Shropshire et al., *Advanced Fuel Cycle Cost Basis*, p. F1-17.

168 Shropshire et al., *Advanced Fuel Cycle Cost Basis*, p. F2/D2-18.

169 Shropshire et al., *Advanced Fuel Cycle Cost Basis*, p. D1-5.

170 OECD/NEA, *The Economics of the Back End of the Nuclear Fuel Cycle* (Paris: OECD/NEA, 2013).

171 OECD/NEA, *The Economics of the Back End*, p. 88. This was the outcome for a 3 percent discount rate (remarkably, the only rate higher than zero included in the calculations), at all levels of scale of the nuclear energy enterprise.

fabrication plant with an 800 tHM/yr capacity as being in the range of $9-$15 billion, with a reference estimate of roughly $12.5 billion (2010$; these would be $9.6-$16 billion and $13.4 billion in 2014$). The annual operating costs of a plant at that scale were estimated to be in the range of $530 million to $750 million (2010$, reference estimate $675 million 2014$).[172] These capital and operating costs are similar to those reported for the THORP and UP2-800/UP3 facilities, as described earlier.

Unfortunately, there are a number of problems with the NEA report:

- For its reference cost reprocessing plant, the report uses the 2006 BCG study. As noted above, the BCG estimates are unrealistic. The capital cost estimated in the BCG study and used in the NEA report is much less than any contract price AREVA has ever actually offered to build a reprocessing plant—and in particular far less than the price AREVA has offered to China.
- The study treats the real cost of the French plants at La Hague and MELOX as the high end of what such facilities could cost, without mentioning the Rokkasho plant, the most recent reprocessing plant built, which has been far more expensive.
- The study assumes that a reprocessing plant would operate at 100 percent capacity for an over 50-year operational life, something no real reprocessing plant has ever come close to doing. This significantly reduces the per-kilogram cost of reprocessing used in the study.[173]
- The NEA report uses only 0 percent and 3 percent discount rates for its main cases. Such low costs of money (and little discounting of the cost of direct disposal) are unrealistic except where governments or government-owned firms will be financing the projects, and make reprocessing look much more attractive than it is with higher costs of money. While such low discount rates may be plausible in China, where a reprocessing plant would likely be financed by a state-owned firm, they are unrealistic in many other markets.
- The NEA report assumes that the cost of reprocessing and fuel fabrication for fast reactors will be identical to those for LWRs, despite much higher plutonium concentrations and far higher burnups (both of which typically contribute to higher costs).

172 OECD/NEA, *The Economics of the Back End*, pp. 80–82.

173 OECD/NEA, *The Economics of the Back End*, Figure 3.9, p. 74, and pp. 80-82.

- The study suggests a long-term uranium price of $130/kgU. This is likely higher than the cost of production for the marginal producer needed to fill demand, and is higher than any of the other studies referenced above, making the once-through cycle appear less attractive.

In short, while the NEA study did conclude that the once-through fuel cycle is cheaper than reprocessing and recycling, the real difference is likely to be substantially larger than the NEA study concluded.

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.

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