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China's Spent Nuclear Fuel Management: Current Practices and Future Strategies

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Abstract
Although China's nuclear power industry is relatively young and the management of its spent nuclear fuel is not yet a concern, China's commitment to nuclear energy and its rapid pace of development require detailed analyses of its future spent fuel management policies. The purpose of this study is to provide an overview of China's fuel cycle program and its reprocessing policy, and to suggest strategies for managing its future fuel cycle program. The study is broken into four sections. The first reviews China's current nuclear fuel cycle program and facilities. The second discusses China's current spent fuel management methods and the storage capability of China's 13 operational nuclear power plants. The third estimates China's total cumulated spent fuel, its required spent fuel storage from present day until 2035, when China expects its first commercialized fast neutron reactors to be operational, and its likely demand for uranium resources. The fourth examines several spent fuel management scenarios for the present period up until 2035; the financial cost and proliferation risk of each scenario is evaluated. The study concludes that China can and should maintain a reprocessing operation to meet its R&D activities before its fast reactor program is further developed.
Keywords: China; Nuclear spent fuel; Reprocessing

1. Introduction

China's declared nuclear energy ambitions put it at the forefront of research and development in the nuclear industry. In the past several years, China has made an extraordinary commitment to nuclear energy development. It currently has 13 commercial nuclear power plants, a small stake compared to the 104 operational reactors in the United States and the 59 operational reactors in France, but its nuclear energy output is expected to grow substantially in the coming decades. Currently, 25 nuclear reactors are under construction in China, a total that accounts for almost 40 percent of the nuclear power plants under construction worldwide (WNA, 2011). In March 2008, the National Development and Reform Commission (NDRC) suggested that the Chinese installed nuclear power capacity could exceed 70 GWe by 2020 due to faster than expected construction (China Daily, 2008).

As part of its nuclear energy policy, China is moving forward on its commitment to operate a closed nuclear fuel cycle, a policy that was first articulated in the 1980s. China's main rationale for a closed fuel cycle that includes the capability to reprocess spent nuclear fuel has been its inadequate supply of uranium resources (Xu, 2008). However, for reasons that will be discussed later, China is likely to have enough uranium from both domestic production and imports to satisfy nuclear fuel demands in the next several decades. As it considers what type of reprocessing program it should pursue in the long-term, China would do well to consider a range of options.

In general, China's decision to reprocess its spent fuel was made with an absence of transparency and a lack of public and outside expert input. In the absence of these inputs, current strategies could bear the influence of the nuclear industry's commercial interests. In the hopes of influencing Chinese fuel cycle development, this study explores China's long-term options for managing the back-end of its nuclear fuel cycle by examining China's spent fuel storage capability, uranium resources, fast reactor R&D capability, and the cost and proliferation risks of each option.

This paper is divided into four sections: the first discusses alternate spent fuel management strategies and current Chinese' spent nuclear fuel storage practices; the second examines China's current nuclear fuel cycle program and its reprocessing policy; the third estimates the likely natural uranium inputs and spent fuel outputs of China's expanding nuclear energy sector, as well as the amount of spent fuel storage that could be required; the fourth develops various different long-term spent fuel management and reprocessing scenarios and analyzes the financial costs and proliferation risks of each scenario.

2. Spent Fuel Management: International approaches and China's practices

2.1 International approaches to spent nuclear fuel

Countries with nuclear energy programs employ various spent fuel management strategies. Overall, there are three major approaches: direct disposal, reprocessing, and the export of spent fuel. Direct disposal requires that a geological repository be built for permanent storage. However, no such repository has been built in the world. Countries with a direct disposal policy currently store their spent fuel in on-site or off-site interim storage facilities. As described above, reprocessing spent fuel aims to recover uranium and/or plutonium from the fuel and use them to manufacture future nuclear fuel. In addition, reprocessing spent fuel and burning the resulting fuel in fast-reactors can help reduce the volume and radioactivity of high-level waste. Still other countries decide to transport spent fuel used in domestic reactors abroad to countries that can either store or reprocess it. If this fuel is reprocessed, the resulting high-level wastes are typically transported back to the exporting country. According to a survey completed by Per Hogselius (2009), 13 of the world's 32 countries with commercial nuclear energy programs have a direct disposal policy, while 6 countries have decided to follow the reprocessing route. The remaining countries either have not decided on a policy or export their spent fuel to others.

A country's spent fuel management policy is affected by a range of factors, such as domestic uranium resources, geological conditions, and political systems. In some countries, one factor weighs more heavily than others on policy decisions, while in others, several factors contribute together to the decision. For example, the United States changed its spent fuel management policy to direct disposal as a consequence of India's 1974 nuclear test, which used plutonium separated from Indian spent fuel. In this instance nonproliferation concerns were the major contributor to the policy shift. In contrast, Japan's long-term commitment to reprocessing and the recent construction of domestic reprocessing plants could be interpreted as a result of a complex array of factors, including its domestic political system, geological conditions, and energy security policy (Hogselius, 2009: Katsuta and Suzuki, 2009).

2.2 China's current spent fuel management strategy

More than three-fourths of the number of reactors built to date in the world went online before 1990, while all of China's reactors went online after 1990. In general, the spent fuel storage capacity at operational Chinese nuclear power plants built before 2005 can accommodate 10 years of spent fuel.

China's first nuclear power plant, Qinshan Phase I, went online in 1991 and has started to accumulate more spent nuclear fuel than it has the capacity to store. To ease the problem, the plant is using dense-pack racks in its spent fuel pools.[1] In addition, in 2009, Qinshan Phase I was approved to expand its spent fuel storage pools to accommodate more fuel. The current plan is to enlarge the no. 2 on-site spent fuel pool, which will extend the storage capacity to 2025. [2]

Chinese officials are also considering dry-cask storage as an alternate solution. Qinshan Phase III started constructing an on-site interim dry-storage facility in 2008 (CAEA, 2009). It plans to construct 18 MACSTOR-400 concrete storage modules at a rate of 2 modules every 5 years, which could expand the on-site spent fuel storage capacity to 40 years (Zheng et al., 2005).

The other site with spent fuel storage challenges is Day Bay Power Plant. To address the shortage of storage, in September 2003, the Daya Bay plant sent spent fuel to a temporary storage pool at the pilot-scale test reprocessing plant in GanSu province. Since then, the plant has transported 104 assemblies of spent fuel twice a year to the interim storage pool. To transport the fuel, Chinese officials pack the spent nuclear fuel in NAC-STC type spent fuel containers, which can fit at most 26 fuel assemblies per container (NNSA, 2003). Table 1 shows the current status of spent fuel storage at each operational Chinese site prior to the expansion of on-site capacity.

Table 1. The current status of spent fuel storage at PWRs in China

NNP Name	Unit No.	Date of First Connection to the Grid	Spent fuel storage method	On-site spent fuel storage capacity	Year when storage capacity will be filled up
Qianshan		12/15/1991	Dense-pack wet Pool size expansion	35 years	2025
Daya Bay	Unit 1	08/31/1993	Wet storage	10 years	2003
	Unit 2	02/07/1994			2004
Qinshan Phase II	Unit 1	02/06/2002	Dense-pack wet	20 years	2022
	Unit 2	03/11/2004			2024
LingAo	Unit 1	02/26/2002	Dense-pack wet	20 years	2022
	Unit 2	09/14/2002			2022
Qinshan Phase III	Unit 1	11/19/2002	On-site wet/dry storage	40 years	2042
	Unit 2	06/12/2003			2043
Tianwan	Unit 1	05/12/2006	Wet storage	20 years [3]	2026
	Unit 2	05/14/2007	Dense-pack wet Pool size expansion		2027

[1] Personal communication with personnel in the Fuel Management Section at Qinshan Nuclear Power Plant, February 21, 2008.
[2] Personal communication with personnel in the Fuel Management Section at Qinshan Nuclear Power Plant, December 13, 2009.
[3] Newly planned reactor designs include a 20-year on-site spent fuel storage capacity.

3. China's nuclear fuel cycle program and reprocessing policy

3.1 *China's nuclear fuel cycle program*

During the 1960s, China developed a complete industrial nuclear science and technology infrastructure as part of its nuclear weapon program. As the successor to the ministry that oversaw the weapons program, the China National Nuclear Corporation (CNNC) maintains China's only nuclear fuel fabrication facilities, domestic uranium exploration and mining capabilities, and uranium enrichment and reprocessing facilities. CNNC currently has eight uranium mining and metallurgy limited liability companies, which own more than 200 uranium mines in China (NNSA, 2005). Table 2 lists all eight companies and their major subordinate mines.

Table 2. Major uranium mining companies in China

Name	Province	Major mines	Type
Fuzhou JinAn	Jiangxi	Xiangshan	Volcanic deposit
		LeAn	Volcanic deposit
Ganzhou JinRui	Jiangxi	Taoshan	Granite-hosted deposit
Zhejiang Quzhou	Zhejiang	Quzhou	Volcanic deposit
Shaoguan Jinhong	Guangdong	Wengyuan	Granite-hosted deposit
Shaoguan Jinyuan	Guangdong	Chenzhou (Hunan Province) Dapu (Hunan)	Granite-hosted deposit
Xi"An LanTian	Shannxi	LanTian	Granite-hosted deposit
Xinjiang Tianshan	Xinjiang	Yili Basin Yining	Sandstone-hosted deposit Sandstone-hosted deposit
Beifang	Liaoning	Benxi	Sandstone-hosted deposit
		Qinglong (Hebei)	Volcanic deposit
		Chifeng (Inner Mongolia)	Sandstone-hosted deposit

(Source: CNNC yearbook, 2004)

From the limited amount of information that is publicly available, it seems that China had three uranium conversion plants, which have an annual capacity of 500-800 tU per plant (Zhou et al., 2002). In addition to these three small plants, China also operates a 3,000 tU per year capacity plant with wet-process technology. This plant had its first test run in 2008 (CAEA, 2008).

According to public information, China currently has two commercial enrichment plants: the Hanzhong enrichment plant in Shaanxi Province, which has an enrichment capacity of 0.5 million separative work unit (SWU) per year, and the Lanzhou enrichment plant in Gansu Province, which has the same capacity. Both of these plants' centrifuges were adopted from Russian technology. China will add another 0.5 million SWU of capacity at the Hanzhong plant in 2010 (TENEX, 2007). Figure 1 shows China's major uranium reserve areas and enrichment facilities (OECD and IAEA, 2009).

Figure 1. China's uranium mines and enrichment facilities

Two nuclear fuel manufacturers currently provide nuclear fuel assemblies for China's commercial fleet of nuclear power plants, excluding the Tianwan Phase I reactor. The Yibin Fuel Plant located in Sichuan Province provides all nuclear fuel and control rod assemblies for Qinshan Phase I and II, Daya Bay, and LingAo nuclear power plants; the Baotou Fuel Plant in Inner Mongolia provides nuclear fuel assemblies for the Qinshan Phase III (two CANDU units) nuclear power plant. The Yibin plant uses the Advanced Fuel Assembly (AFA) streamlined fuel production process, which it adapted from the French, and produces 4.45 percent, 3.7 percent, 3.4 percent, and 3.25 percent enriched uranium fuel (NNSA, 2006). In 2005, it produced a total of 378 fresh nuclear fuel assemblies (NNSA, 2006). The plant also plans to produce M5 AFA 3G high-burnup fuels for China's domestic Gen II+ reactor design, the CPR1000, which China intends to operate with an 18-month fuel reloading requirement. In preparation for higher demand, it expanded its manufacturing capability to 400 tons per year in 2008 (People's daily, 2008).

China built a VVER-1000 fuel element manufacturing line to supply the Sino-Russian reactors in its fleet with recent technology transfers from Russia. The line manufactured its first set of fuel elements for Tianwan unit 1 and 2 in October 2010 at the Yibin fabrication plant (CNNC, 2010). China began building an AP1000 streamlined fuel production line at the Baotou fabrication plant in March 2008. Production of AP1000 fuel assemblies is scheduled to start in 2013, with the initial fuel load being delivered in 2014. The total annual manufacturing capability of the production line is expected to be 800 tons.[4]

3.2 *China's reprocessing policy*

China first decided to develop a closed nuclear fuel cycle in the early 1980s. With an anticipated shortage of uranium supplies and limited uranium exploration activities, China said that it wanted to able to reprocess spent nuclear fuel from its commercial light-water reactors (LWR), extract the resulting uranium and plutonium, and use them to fabricate nuclear fuel for use in fast breeder reactors. In 1986, the State Council approved the construction of a pilot-scale test reprocessing plant with annual reprocessing capability of 50 tons at the 404 factory in GanSu Province. Nearly 25 years later, the pilot-scale plant is nearing operation. Chinese scientists conducted a hot test at the facility in December 2010 (CNNC, 2010). The plant contains an interim spent fuel storage facility on site with a storage capacity of 550 tons of fuel (500 tons for commercial reactors and 50 tons for research reactors).

China initially planned to build a commercial-scale reprocessing plant with a capacity of 800 tons per year by 2020, but it has yet to decide on a location for the plant. China is still negotiating with the French consortium Areva on the plant's purchase, and its operation is likely to be postponed until 2025, at the earliest (Deng, 2010).[5]

China's development of fast-neutron reactors has similarly fallen behind schedule. China expects fast neutron reactors to become the predominant commercial reactor type in operation around the country by mid-century. To get there, it plans a three-stage development process that started with a 20-MWe (65 MWt) experimental fast neutron reactor (CEFR) project that is currently in operation at the China Institute of Atomic Energy (CIEA) (see table 3) (Xu, 2008). The reactor conducted its first startup in July 2010 (Xinhua news, 2010). The CIEA project mainly relies on fast reactor technologies developed from the Russian BN-600. The design accommodates MOX fuel, which bridges the gap between the types of fuel used in light water reactors and fast neutron reactors. The development of two demonstration fast reactors (CDFRs) makes up the second stage of the development process. In October 2009, China signed a high-level agreement with Russia to collaborate on the development of two BN-800 fast neutron reactors (CNNC, 2010). Construction on these reactors is expected to start in August 2011 (WNN, 2010a).

[4] "Introduction of Northern Fuel Fabrication Corporation," CNNC, available at http://www.cnnc.com.cn/202zn.htm.
[5] Personal communication with Zhongmao Gu in the reprocessing program at CIAE, March 15, 2010.

Before commercializing fast neutron reactors, China plans to construct a commercial MOX fuel fabrication site by 2020 to couple with the proposed commercial reprocessing plant. The manufacturing of MOX fuel is a crucial step in the development process because it will permit China to use the separated uranium and plutonium that results from reprocessing and provide feed fuel to its CEFR and CDFRs. A pilot-scale MOX manufacturing facility with an annual capability of 0.5 tons is currently under construction. China is exploring potential partnerships to develop MOX fuel manufacturing projects with Areva.[6]

Table 3. China's three-stage development of fast neutron reactor

	Reactor type	Power level (MWe)	Construction plan	Fuel type
The first stage	Experimental fast reactor (CEFR)	20	2009	UO_2 (first load) MOX
The second stage	Demonstration fast reactor (CDFR)	800 ~ 900	2020~2025	MOX Metal alloy
The third stage	Commercial fast breeder reactor (CCFR)	≥900	2030~2035	Metal alloy

4. China's future uranium demand and access, and spent fuel outputs

4.1 *Future uranium demand in China*

Considering that China has justified its decision to reprocess its spent nuclear fuel on the grounds that it needs to create a secure source of fuel for nuclear power generation, it's worth examining how China's access to uranium resources is expected to match up with demand in the coming decades. This study considers three nuclear expansion scenarios to estimate China's future uranium demand. The first scenario is the reference case and is based on China's current long-term nuclear power development plan, which anticipates that nuclear power will have a 20-percent share (the current world nuclear share) of the total national installed capacity by 2050. The second scenario is a high-growth scenario, which anticipates continuous nuclear expansion and a 30-percent nuclear share of installed capacity by 2050. The third scenario is the low-growth scenario, which anticipates a 10-percent nuclear share by 2050.

These scenarios all assume that nuclear growth will take the form of additional 1 GWe pressurized water reactors (PWR) and that GenerationIV reactors will be developed to the point

[6] Personal communication with Mi Xu in the CEFR program at the CIAE, March 15, 2010.

that they are commercially deployable by 2040. The study assumes that the nuclear portion of the installed generating capacity will be 150 GWe, 300 GWe, and 450 GWe for the three different growth scenarios, respectively (Zhou, 2010). These projections are comparable to those in China's 863 Energy Plan (Zhao, 2000).

To calculate the amount of natural uranium that will be required to support China's nuclear expansion during the coming decades, this study breaks down the history and future of Chinese commercial reactor operation into three time periods: from 1991 to 2006, from 2007 to 2020, and from 2021 to 2035. When examining the first period, historical data are used. Nine PWRs in operation before 2005 are assumed to have an average burn-up rate of about 33 GWd/t and a capacity factor of 85 percent. During the second period (2007-2020), the study assumes that rapid growth leads to a nuclear capacity of 60 GWe by 2020; that nuclear capacity grows exponentially during the period; and that existing and planned PWRs achieve a burn-up rate of about 50 GWd/t, with a capacity factor of 85 percent. The third period (2021-2035) looks at the demand under each of the three potential growth scenarios described above: the reference scenario, the "high-growth" scenario, and the "low-growth" scenario. The newly designed Gen III PWRs are assumed to achieve a 65-GWd/t burn-up rate, while existing PWRs from before are assumed to operate with a 50 GWd/t burn-up rate. Linear growth is assumed during this period for each scenario, and reactor types other than light water reactors (LWR) are not considered for simplicity in calculations.

The total mass of annual fuel required for each of the nine PWRs which started operating before 2006 is approximately 28.5 metric tons of heavy metal (again, assuming an average capacity factor of 85 percent and a thermal efficiency of 33 percent). The newly constructed and planned PWRs might achieve a higher burn-up rate of about 50 GWd/t, with the same capacity factor and thermal efficiency. This higher burn up rate would reduce the mass of annual fuel required in one 1-GWe PWR to approximately 18.8 tons. The new Gen III reactors that are expected to come online after 2020 are assumed to have a burn-up rate as high as 65 GWd/t, which would lower the mass of annual fuel required in one 1-GWe reactor to 14.5 tons (with the same capacity factor and thermal efficiency).[7]

[7] The mass of annual fuel required in metric tons of heavy metal (MTHM) that must be loaded into one PWR reactor is obtained as:

$$M = \frac{P \times CF \times 365}{\eta_{th} \times B}$$

where
M: mass of annual fuel loaded per year (MTHM/year);
P: installed electric capacity (GWe)
CF: capacity factor
η_{th}: thermal efficiency (GWe/GWth),
and B: discharge burnup (GWd/MTHM)

The total mass of annual fuel loaded into Chinese reactors can thus be determined by combining the initial fuel load at newly constructed nuclear power plants and the annual fuel load at existing nuclear power plants.[8] The mass of natural uranium required for fuel production can be obtained by considering the enrichment process.[9] Table 4 estimates the amount of natural uranium that would be required for three growth scenarios.

Table 4. Total amount of natural uranium required by 2035

Cumulated natural uranium (tons) 2006~2020		Cumulated natural uranium (tons) 2021~2035		Total (tons)
The Rapid Growth (60 GWe)	86719	Reference scenario (450 GWe)	363972	450691
		High growth scenario (300 GWe)	488333	575052
		Low growth scenario (150 GWe)	239611	326330

4.2 Potential domestic and oversea access to uranium

According to the Chinese Atomic Energy Authority (CAEA), China had an estimated 100,000 tU of uranium resources in the < $130/kgU category in 2007 (CAEA, 2007). China currently imports one third of the uranium fuel it needs and manufactures one-third from domestically mined uranium. To fill its remaining needs, it manufactures fuel from uranium ore purchased overseas.[10] If it continues to obtain fuel from these sources in the same proportion that it presently does as demand increases and if the international uranium market remains stable, the domestic reserves claimed could last for the next 20 years based on the growth scenarios assumed above and the calculations in Table 4.

[8] The annual fuel load for a 1-GWe newly constructed PWR is approximately one third of the initial fuel load of the reactor.

[9] The mass of natural uranium required for fuel production can be obtained by considering the enrichment process. The required enrichment level for a given burn up can be calculated given the amount of feed material (natural uranium 0.711 percent) by**:**

$$F = p \times \left(\frac{x_p - x_w}{x_f - x_w}\right)$$

Where;

x_f = weight fraction of U-235 in the natural uranium; here, x_f = 0.711percent

x_p = weight fraction of U-235 in the enriched uranium fuel; here, x_p = 3.2percent, 4.5percent and 5percent for 33 GWd//t, 50 GWd/t and 65 GWd/t burnup rates respectively.

x_w = weight fraction of U-235 in the waste stream; here, x_w = 0.3percent

F = the amount of natural uranium

P = the amount of product enriched

[10] Personal interviews with personnel from INET at Tsinghua University, China Institute of Atomic Energy (CIAE), and CNNC (names withheld by request), January 2008.

After China committed to developing its nuclear energy program, it proposed strengthening its domestic uranium exploration and mining operations. As part of the "11th Five-year Plan," China proposed, for the first time, adopting national strategies to effectively access domestic and oversea natural uranium reserves. The CNNC set up the China National Nuclear Overseas Uranium Resources Development company (NNOURD) to seek out and invest in overseas resources in 2006. In April 2006, China signed a deal with Australia that is expected to lead to 20,000 tons of uranium exports to China annually (BBC, 2006). Similarly, a 2004 deal with Canada on energy cooperation, included access to Canada's oil sands and uranium mines (Bloomberg, 2004). While NNOURD claims to have secured more than 200,000 tons of uranium reserves in total in Africa, Australia, Canada, and Central Asia, the China Guangdong Nuclear Power Corporation (CGNPC) has also invested heavily to ensure that it has sufficient nuclear fuel supplies. CGNPC invested in China's first uranium mining project in Kazakhstan in 2009. In addition, Areva and Cameco signed nuclear fuel agreements with CGNPC to supply it with uranium fuel over the next decade (CGNPC, 2009; WNN, 2010b; WNN, 2010c). These and other Chinese investments in foreign uranium production will significantly help China meet its fuel demands for the next several decades.

On the mining side of the equation, the CNNC has significantly increased uranium exploration activities. In 2008, the CNNC, the only state-owned nuclear corporation with uranium exploration and mining capabilities, announced that it had discovered China's largest uranium ore deposit in the northern Inner Mongolia Autonomous Region and China's largest Sandstone-hosted deposit at Yili basin in the Xinjiang Autonomous Region (People's daily, 2008; Xinhua news, 2008). The OECD and IAEA's *Uranium 2009: Resources, Production and Demand*, also known as the "Red Book," reports that the newly discovered uranium resources amount to a total of about 71,400 tU categorized as reasonable assured resources (RAR) and inferred resources (IR), lifting China's uranium resources to 171,400 tU (RAR and IR).

In addition, China can easily build up its stockpiles of nuclear fuel from the international uranium market. According to the 2007 Red book, Earth has an estimated 5.4 million tons of global "identified uranium resources," 70 times the global production of uranium estimated for 2007. In addition, the IAEA estimates that there are 10.5 million tons of "undiscovered resources," 140 times the global production for 2007 (IAEA, 2008). Nations are also likely to explore unconventional uranium sources, such as those in phosphate rocks (22 million tons that are recoverable as by-products) and seawater (4 billion tons are recoverable at an estimated cost of $240~450/kgU), when cheap uranium sources become scarce and uranium prices increase (Bunn et al., 2003).

In general, uranium deposits are thought to be geographically more evenly distributed than any other energy resource, though a relatively few countries—including Australia, Canada, and countries in Central Asia—hold the largest share of the most economical, high-grade uranium ores. Given this distribution, the risk of supply disruption is minimal compared to oil and natural gas reserves, which are disproportionally concentrated in the Middle East (EIA, 2009). In addition, countries can maintain stockpiles of nuclear fuel with relative ease, given that uranium fuel storage requires far less space than do fossil fuels. Lastly, nuclear fuel costs are only about 5 percent of the total generating costs of a reactor, while fuel costs for coal-fired and natural gas-fired plants make up to 40 percent and 60 percent of costs, respectively (NEA, 2008). The newly released MIT report of the future of the nuclear fuel cycle (2010) concluded and confirmed that there is no shortage of uranium resources that might constrain future commitments to build new nuclear plants for much of this century at least (MIT, 2010). All of these arguments suggest that the availability of nuclear fuel is unlikely to constrain future nuclear expansions, in China or elsewhere.

4.3 *Future spent fuel management*

Chinese reactors accumulated about 1,100 tons of spent fuel from 1991 to 2005, according to multiple sources (Liu et al., 2006). The amount of spent fuel that is expected to be unloaded between 2006 and 2020 can be estimated by calculating the mass of fuel loaded into one PWR reactor annually. Table 5 estimates the amount of spent fuel that will accumulate by 2035 for each nuclear growth scenario.

As discussed before, new Chinese plant designs include on-site spent fuel storage with a capacity of 20 years worth of spent fuel. To simplify calculations, this study assumes that on-site spent fuel storage is fully occupied before spent fuel needs to be transported to off-site storage facilities. Under these parameters, operational nuclear plants will have sufficient on-site storage for spent fuel until 2020, except for the Daya Bay nuclear plant. (Daya Bay annually sends 104 assemblies to the interim spent fuel storage pool at the pilot reprocessing site.) After 2020, current plants will gradually run out of space for spent fuel storage. These reactors and any others that are constructed before 2015 will need off-site spent fuel storage space. By 2035, the total amount of spent fuel that will need to be stored off-site will reach 1,686.5 tons. Figure 2 shows the cumulative off-site spent fuel storage that will be needed from 2005 to 2035, as well as off-site storage capacity options. The 500-ton off-site spent fuel storage facility at the pilot reprocessing site should fulfill China's storage needs until 2017. Additional interim spent fuel space will be required thereafter.

The MIT report concluded that the long-term managed storage of spent fuel is safe and economical for about a century (MIT, 2010). As such, China could fulfill its need for off-site storage by building another interim spent fuel storage pool; a 3,000-ton pool would satisfy the need for extra space up until 2035. Indeed, China is considering building a 3,000-ton spent fuel storage pool as part of its commercial reprocessing plant (Deng, 2010). The combination of additional off-site storage and plans to include ample on-site storage at new nuclear plants, suggests that China will experience little pressure to reduce the burden of storing spent fuel in the next 30 years.

Table 5. Cumulated spent fuel generated from 1994 to 2035

	1994~2005	2006~2020	2020-2035	
Cumulated spent fuel (tons)	1100	6579 *	Reference scenario (300 GWe)	17656
			High growth scenario (450 GWe)	21643
			Low growth scenario (150 GWe)	13668

*Spent nuclear fuel generated from 2006 to 2020 is generated by nuclear power plants that began operating before 2005.

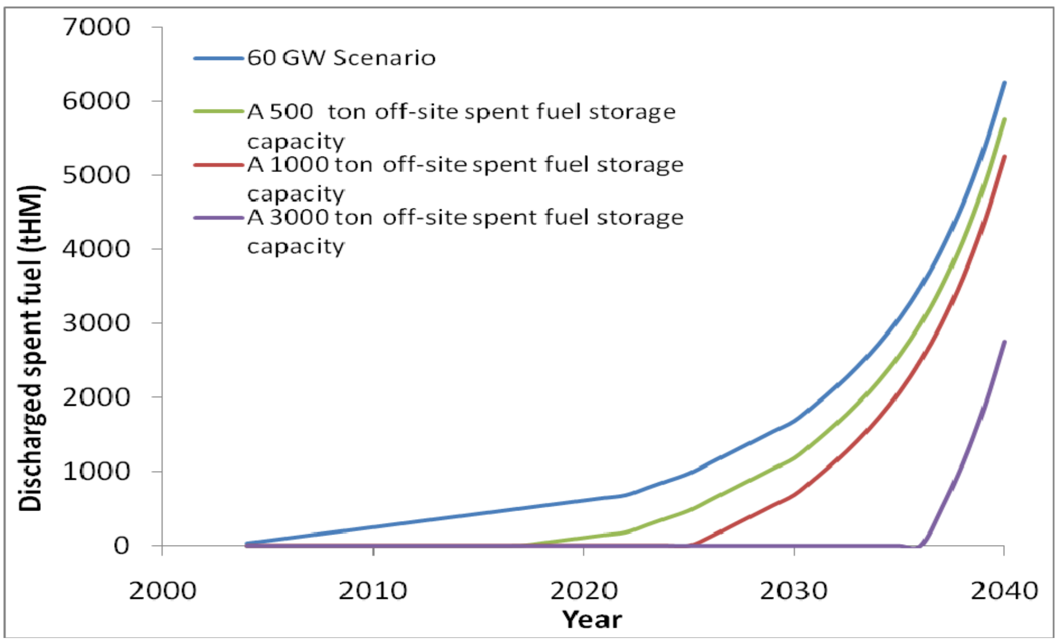

Figure 2. Cumulative additional storage demands with three different storage scenarios from 2003 to 2035 in China.

5 China's future nuclear fuel cycling scenarios and analyses

As discussed in earlier sections, nuclear waste and spent fuel management are not yet major concerns for China's relatively young nuclear industry. Though China has a long-standing policy to eventually reprocess its spent nuclear fuel, due to the long-term construction period, huge investments involved, and technology immaturity, various uncertainties make the reprocessing and fast reactor programs still unforeseeable. Taken together with the fact that it is likely to have sufficient spent fuel storage at reactor sites for at least the next 30 years**,** China has the opportunity to evaluate anew a range of long-term spent fuel management scenarios and decide on the best solution, taking into account economic, safety, and security issues.

5.1 *China's future nuclear fuel cycling scenarios*

This analysis examines three spent fuel management options that China could implement between now and its expected commercialization of fast reactors in 2035 and that would address China's long-term fuel-cycle needs:

1) **No reprocessing scenario.** In this scenario, Chinese reactors send all spent fuel that they can't store onsite to off-site interim dry or wet storage.

2) **A need-based reprocessing scenario.** This scenario assumes that China will start reprocessing spent fuel at a rate of 50 tons per year in 2011 and reprocess additional fuel based on its needs to fulfill its fast reactor program. The separated plutonium will be used to manufacture MOX fuel for both the CEFR and CDFR programs and metal fuel for future China Commercial Fast Reactors (CCFRs). The reprocessing program will produce as much plutonium as is needed to provide fuel for the CEFR and CDFR, while trying to avoid the unnecessary stockpiling of plutonium.

Russia provided the initial fuel load for the CEFR, which began operation in 2010**,** because of the delay in construction of China's pilot-scale reprocessing plant. This scenario assumes that China will provide all subsequent annual fuel loads for the CEFR, even though the status of the MOX manufacturing pilot plant is unclear. The CEFR's annual fuel requirements are 150 kilograms of plutonium, while the two CDFRs need 3.6 ton of plutonium annually.[11] In this scenario, it assumes that China will provide the fuel for the CDRRs, though it is quite likely that Russia will supply the initial fuel for these reactors.[12] Approximately 375 tons of spent fuelneed to be reprocessed annually to meet the demand for the CEFR and two CDFRs.[13]

In addition, China needs to produce plutonium for its future CCFRs. According to the CNNC proposal, China plans to build between five and six CCFRs by 2030; six CCFRs would require about 12 tons of plutonium for their initial fuel loads. In order to limit the stockpiling of plutonium, China could start by reprocessing 50 tons annually from 2011 to 2024. This would provide sufficient fuel for the CEFR and the initial loads for the first two CDFRs. China's reprocessing capacity would have to increase to 400 tons per year to supply the CEFR and

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[11] Personal communication with Mi Xu from the CEFR program in the CIAE, March 2010

[12] Ibid.

[13] These calculations assume that plutonium accounts for 1percent of spent fuel and that the MOX fuel used in fast neutron reactors consists of 30 percent PuO_2.

CDFRs thereafter. China would have to start reprocessing around 800 tons per year by 2034 in order to prepare enough fuel for the initial 5 CCFRs' fuel loads.

3) **A capability-based reprocessing scenario**. In this scenario, China would operate its reprocessing facilities at 100-percent capacity. China's pilot-scale reprocessing facility and its as-yet-unbuilt commercial-scale facility, could give China the capability to start reprocessing 800 tons of spent fuel per year as soon as 2025. There are two possibilities for the separated plutonium generated by this level of activity: one is to store the separated plutonium using proliferation-resistant measures (the plutonium stockpile case); the other is to recycle the separated plutonium as MOX fuel into LWRs (the MOX fuel case). The problem with MOX fuel is that it is more costly than using traditional LEU fuel under current economic conditions. Table 6 outlines each scenarios'key activities. Figure 3 plots the scenarios' reprocessing activities as a function of time.

Table 6. Key reprocessing-related activities during 2010-2035, and three spent fuel management scenarios

2010-2024	2025-2034	2035~
Gen II+ PWRs The pilot reprocessing site (50 tons/yr) The pilot PWR-MOX fuel plant (0.5 tons/yr) The CEFR connecting to grid (20 MWe)	Gen III/Gen II+ PWRs The commercial reprocessing site (800 tons/yr with a 3000 ton interim spent fuel storage pool) The commercial MOX fuel plant (40 tons/yr) Two CDFR constructed (800~900 MWe)	Gen III PWRs/Gen IV 5~6 CCFRs constructed (800~900 MWe)
Scenario 1: No reprocessing activities; all off-site spent fuel stored in interim pools/dry storage	Dry/wet storage, no reprocessing	Dry/wet storage, no reprocessing
Scenario 2: Reprocessing 50 tons/year; manufacturing MOX 0.5 tons/year;	reprocessing 400 tons/year[14] for both the CEFR and CDFRs from 2025 to 2033; reprocessing 800 tons/year for CEFR, CDFRs and CCFRs from 2034 Manufacturing MOX 12.5 tons/year for both the CEFR and CDFRs from 2011 to 2035	Continue reprocessing and manufacturing MOX fuel to accommodate its research and commercial fast reactors.
Scenario 3: Start reprocessing 50 tons/yr; manufacturing MOX 0.5 tons/year.	Start reprocessing 800 tons/year in 2025; Manufacturing MOX 12.5 tons/year 2025 to 2034 for both the CEFR and CDFRs. China can either recycle separated Pu as MOX fuel for LWRs or simply store it	Continue reprocessing 800 tons/year and manufacturing MOX fuel 40 tons/year

[14] The annual MOX fuel load for the CEFR is 0.5 ton and the annual MOX fuel load for one CDFR is 7.5 tons, based on an 850-MWe power level, a 100-GWd/t burn-up rate, a 33-percent thermal efficiency, and an 80-percent capacity factor.

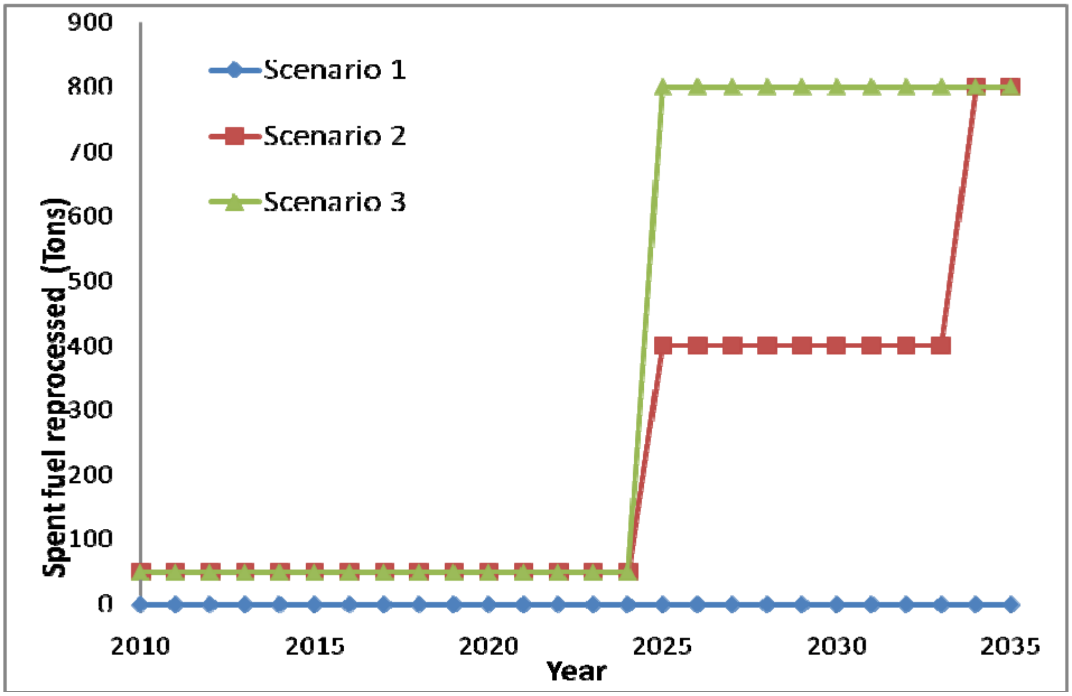

Figure 3. Amount of spent fuel reprocessed in three scenarios.

5.2 *Financing costs and proliferation risks*

Chinese nuclear experts are aware that reprocessing spent fuel and recycling separated plutonium is more expensive than the once-through fuel cycle where spent fuel is directly disposed and that this difference is likely to persist for the next several decades.[15] They argue that as uranium prices increase and uranium resources are depleted, reprocessing and recycling is the only way to maximize energy outputs from limited uranium resources and to keep China's energy development sustainable, a long-term goal of China.

Although China's booming economy could help to ensure enough capital investment into its fast reactor and nuclear fuel cycling programs in the short term, all countries with nuclear energy programs consider economics when deciding whether to pursue a reprocessing capability (Hogselius, 2009). This section provides a simple cost analysis of the three spent fuel management scenarios outlined in the previous section, based on newly released economic data from the Idaho National Laboratory (2009) given in Table 7 (Shropshire et al., 2009). Although the economics of reprocessing, spent fuel storage, and geological storage are all likely to be different in China compared to the United States due to different capital and labor costs, the qualitative picture is unlikely to be different because all costs would be expected to be proportionally lower, albeit with differences due to distribution between capital and labor costs. In scenario 1, dry storage is assumed to be an interim solution. The costs associated with this strategy primarily include building dry storage facilities. In general, a once-through fuel cycle

[15] Personal communication with Mi Xu from the reprocessing program in the CIAE, March 2010.

leads to spent fuel being placed in a permanent geological repository after a dry-storage period. However, in this study, scenario 1 does not necessarily imply a once-through fuel cycle. Dry storage can postpone the costs of either reprocessing or direct disposal and leave open all options as economics and technologies evolve. These dry-storage costs include the cost of transporting spent fuel from nuclear plants after on-site storage fills up. This is expected to happen at some sites starting in 2017. In scenario 2, the costs would include operating reprocessing and MOX fabrication facilities.

Scenario 3 suggests two possible outcomes for the plutonium that is separated through reprocessing. Either outcome will add costs to the expense of reprocessing and MOX fuel fabrication for the CEFR and CDFRs. Though recycling separated plutonium as MOX fuel uses elements of already manufactured fuel, the derived savings cannot offset the fabrication costs of MOX and the material costs of natural uranium. The cost of MOX fuel fabrication is $1,950 per kgHM, while the cost of traditional LEU fuel is $1,640 per kgU, assuming a natural uranium price of $100 per kilogram.[16]

Table 7. Costs for different items in nuclear fuel cycle (2008 U.S. $)

Items	Unit	Value
Conversion processes	$/kg Natural U	10
Enrichment	$/kgU Natural U	105
UO_2fuel Fabrication	$/kg LEU	240
Reprocessing (including waste handling)	$/HM	2160
MOX fabrication	$/HM	1950
Dry Storage of Spent Fuel	$/HM	120

To store the separated plutonium for later use requires a well-designed storage system that ensures the safe storage of the material, and a highly sophisticated and robust material protection, control, and accounting systems to mitigate proliferation threats and security risks. Little information is available about the costs of such a system. Bae (2001) estimated that an international long-term plutonium storage facility with a capacity of 100 metric tons would run

[16] The costs of low-enriched uranium fuel include the cost of the natural uranium, the cost of converting that uranium from the form in which it is mined to the form in which it is enriched, the cost of enriching it to a level usable in the reactor, and the cost of fuel fabrication.

$504 million in construction costs and $30.7 million in annual operation & maintenance costs (in 2000 U.S. dollars). China's plutonium stockpile is not expected to grow to 100 metric tons before it commercializes its fast reactors, yet it will still need an interim storage facility with a capacity of 50 metric tons (see Table 8).

Table 8. Reprocessed spent fuel and separated plutonium, by 2035, in three scenarios

Scenarios	Spent fuel reduced (tons)	Plutonium produced (tons)	Cumulative unused Plutonium (tons)
Scenario 1	0	0	0
Scenario 2	5900	58.9*	14.4
Scenario 3 (the MOX fuel for LWRs case)	9500	94.9*	35.0**
Scenario 3 (the plutonium stockpile case)	9500	94.9*	50.4***

*For simplicity, it is assumed the 1 percent Pu in spent fuel
** It is assumed China will manufacture MOX fuel for both R&D FRs and LWRs
***It is assumed China will only manufacture MOX fuel for R&D FRs

Table 9 provides the estimated cost of scenario 3 where the plutonium is made into MOX fuel for LWRs and the other two scenarios.[17] Transportation costs are not included in Table 9 due to their relatively small portion of overall fuel cycle costs, accounting for less than 7 percent in both once-through and closed fuel cycles (Shropshire et al., 2009). It shows the likely costs at two different discount rates. At a discount rate of 5 percent, the interim dry storage without reprocessing and recycling (scenario 1) is estimated to cost $123.5 million dollars, which amounts to 2.4 percent of the cost of scenario 2 and 1.4 percent of the cost of scenario 3. The cost of scenario 2 is approximately 62 percent of the cost of scenario 3 at a 5-percent discount rate.

Another major factor that distinguishes the fuel-cycles outlined in the three scenarios is their proliferation risk. The irradiated spent fuel that would be stored in wet or dry storage is extremely dangerous to get near and difficult to transport; the separated plutonium that results from reprocessing is easily taken and transported, which raises serious proliferation concerns. Table 8 shows the amount of separated plutonium that would accumulate under the different spent fuel management scenarios. In scenario 2, besides the initial loads for the 5 CCFRs, China would have 2.4 tons of separated plutonium in storage. In scenario 3, China's plutonium stockpile would increase to around 50.4 tons by 2035 before being used in commercial fast reactors in the minimal MOX fuel case. Subtracting the initial loads of fuel for the CCFRs, China

[17] The study assumes the same fabrication costs of MOX fuel for LWRs and FRs.

would still have approximately 23 tons and 38.4 tons of separated plutonium in the MOX fuel for LWRs case and the plutonium stockpile case, respectively.[18]

Table 9. Cumulative costs for three spent fuel management scenarios (2008 U.S. $M)

	With a 0% discount rate	With a 5 %discount rate
Scenario 1 (no reprocessing/dry storage)	319.1	130.1
Scenario 2 (reprocessing as needed)	13025.8	5595.2
Scenario 3 (reprocessing at the maximum capacity) (the MOX fuel for LWRs case)	21391.7	9088.2

5.3 *Potential delays and consequences*

The three reprocessing scenarios outlined above are based on China's current plans for nuclear energy development. However, in practice, their implementation is unlikely to go as planned. China's commercial fast reactor program depends considerably on the success of the demonstration fast reactor, which relies on sound engineering and construction work, on the purchase agreement with Russia for the BN-800s, and the performance of its own experimental fast reactor.

The construction of the first BN-800 reactor at the Beloyarsk nuclear power station is still ongoing (as of 2009), and financial concerns and questions about fuel economics have halted a range of BN-800 projects during the past several years. In addition, Russia's BN-350 and BN-600 fast reactors have experienced numerous sodium fires during their operation (Saraev, 2009).

The capital costs of these reactors and the cost of plutonium fuel are much higher than the costs associated with the VVER-1000. The estimated cost of BN-800 construction is approximately 40 percent more per kilowatt (KW) (Kostin et al., 2007). In addition, the cost of plutonium fuel in fast reactors is much more expensive than the low-enriched uranium fuel in LWRs. The poor operational records, unproven economics, and immature technologies in use in fast reactors around the world create uncertainties about China's fast reactor commercialization.

China's commercial reprocessing program similarly confronts a range of uncertainties. Only 6 out of 32 nuclear power countries have a policy of reprocessing their spent nuclear fuel, and among these countries' programs there are considerably mixed records. Due to economic and political reasons, Japan has experienced considerable delays in the construction and operation of

[18] The study assumes that the initial fuel load for five CCFRs would require 12 tons of separated plutonium.

its Rokkasho commercial reprocessing plants (Katsuta and Suzuki, 2009). China's own pilot-reprocessing site has encountered many delays since the start of construction in 2002. Considering that China has not finalized its deals to construct a demonstration fast reactor and reprocessing plant with Russia and France and the inherently long construction periods associated with both projects, delays are likely.

Possible delays in the construction and operation of fuel cycle facilities lead this study to consider two alternative scenarios. The two scenarios consider the likely effect of delays in the fast reactor and commercial reprocessing programs. Both scenarios assume that the demonstration fast reactor and the commercial reprocessing site become operational in 2030 and that fast reactors are commercialized in 2040. Tables 10 and 11 present the amount of separated plutonium that would accumulate over time and the costs associated with the two delay scenarios. These costs can be compared to the costs in section 5.1. A quick comparison shows that while the cost ratio of scenario 2 to scenario 3 is approximately 62 percent, the ratio of scenario 4 to 5 is 58 percent, demonstrating that a need-based reprocessing strategy could bring less financial risks.

Table 10. Reprocessed spent fuel and separated plutonium by 2035 in delay scenarios

Scenarios	Spent fuel reduced (tons)	Plutonium produced (tons)	Cumulative unused Plutonium (tons)
Scenario 4	7900	78.9*	15.6
Scenario 5 (the MOX fuel for LWRs case)	13500	134.9*	49.2**
Scenario 5 (the plutonium stockpile case)	13500	134.9*	71.6***

*For simplicity, it is assumed the 1 percent Pu in spent fuel
** It is assumed China will manufacture MOX fuel for both R&D FRs and LWRs
***It is assumed China will only manufacture MOX fuel for R&D FRs

Table 11. Cumulative costs for two spent fuel management scenarios with delays (2008 U.S. $M)

	0 percent discount rate	5 percent discount rate
Scenario 4 (need-based reprocessing)	17467.7	6668.9
Scenario 5 (capacity-based reprocessing at the maximum capacity)	305421.7	11572.6

6 Conclusions

This study reviews China's current spent fuel management policies and explores its future spent fuel generation based on three different nuclear energy expansion scenarios. From the spent fuel generation calculations, this study concludes that China will experience very little pressure to lessen the burden of spent fuel storage in the next three decades. It could use on-site/off-site dry storage facilities or current and planned off-site wet storage facilities to meet storage demand, diminishing the impact of this issue on China's reprocessing and recycling programs. In addition, based on current and near-term uranium prices, the economics of reprocessing and MOX fuel fabrication are unattractive and are likely to remain this way for the next several decades. Setting up a fissile material management system and securing unused separated plutonium would pose considerable challenges to China's reprocessing goals.

However, considering China's tremendous projected energy demands, its huge commitment to nuclear energy, its infrastructure of nuclear science and technology, and its estimated uranium resources, it is not surprising that China insists on a *long-term* policy of reprocessing spent fuel and operating fast neutron reactors. The implementation of such a closed fuel cycle will depend on various factors, such as China's technology development, continued economic growth, a consistent national energy policy, and international cooperation on advanced nuclear technologies. After all, reprocessing is still an uneconomical process compared to direct disposal, and fast-reactor technologies are not yet ready for industrial and commercial deployment. Some countries, such as India, Japan, and Russia, are still actively working to commercialize their fast neutron reactors, others, such as German and Britain, have stopped their programs.

As China moves forward, it should focus on when and how it should reprocess, taking into account cost, proliferation risks, uranium fuel security, and spent fuel management issues. To aid this discussion, China could benefit from a decision-making framework that allows for more flexibility and greater variability in order to account for the long timescales inherent in nuclear development. In the short term, China should maintain an active research and development program and sufficient reprocessing operations to meet its demands.

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