China's current spent fuel management and future management scenarios

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Abstract
More than three-fourths of the world's nuclear reactors went online before 1990, while all of China's reactors went online after 1990. Although China's nuclear industry is relatively young and nuclear waste and spent fuel are not yet a major concern, China's strong commitment on nuclear energy and rapid pace on nuclear energy development call for analyses and strategies on China's future spent fuel management. This paper will first discuss the status of China's current spent fuel management methods and storage capability at China's current 11commercial nuclear power plants. Second, this paper will estimate and calculate the accumulated spent fuel and required spent fuel storage up to 2040 based on three different nuclear development scenarios. Third, future spent fuel management scenarios from now to 2040 are designed and financial costs and proliferation risks are evaluated and discussed associated with each scenario. Last, policy recommendations will be provided for the future spent fuel.

Introduction
Although China's nuclear energy program is still at an early stage of development, China's commitment to a closed fuel cycle policy has been maintained since the 1980's. It claims the major driving force for instituting a policy that includes reprocessing policy is its inadequate supply of uranium resource [1]. Since China's nuclear fuel cycle program is under development, which provides opportunities to allow decision makers to plan for the best development, there are few studies providing comprehensive analyses about China's current and future spent fuel management and strategies to develop its spent fuel management policy. However, China's ambitious nuclear development plan promotes the need for research studies on its nuclear fuel cycle program and spent fuel management policy. This study explores potential spent fuel management scenarios based on China's spent fuel storage capability, uranium resources, fast reactor R&D capability, and other factors.

China's current spent fuel management
China now operates 11 reactors with a capacity of 9,118 MWe gross (see Table 1). In general, the spent fuel storage capacity at current pressurized water reactor (PWR) plants in operation was designed to handle 10 years of spent fuel, except the newly constructed Tianwan plant. China's first nuclear power plant, Qinshan Phase I went online in 1991 and it has started to experience problems with over-accumulated of spent nuclear fuel. To ease the problem, Qinshan Phase I is using dense-pack racks [2]. In addition, in 2009, Qinshan Phase I was approved to expand its spent fuel storage pools to accommodate more spent fuel. The current plan is to expand the No. 2 on-site spent fuel pool size, which will extend the storage capacity to 2025 [3]. Dry storage is also being considered as a possible alternative solution for the two CANDU units

since China does not plan to reprocess any spent fuel from CANDU units. Qinshan Phase III started constructing its on-site interim dry storage facility in 2008. It plans to construct 18 MACSTOR-400 concrete storage modules, which could expand the on-site spent fuel storage capacity to 40 years [4][5]. In addition, some spent fuel has already been transported to off-site facilities for interim storage. In September 2003, for the first time, Daya Bay power plant sent spent fuel to the temporary storage pool of spent fuel at the pilot-scale test reprocessing plant in GanSu province. Since then, it has transported spent fuel twice per year with 104 assemblies in total to the interim storage pool [6]. Qinshan Phase II and LingAo units are using dense-pack racks to handle 20 years of spent fuel [7].

Table 1. Operating Nuclear Power Plants in China

NNP Name	Unit No.	Reactor Type	Nominal Power (MWe)	Construction Start Date	Date of First Connection to the Grid
Qinshan Phase I		PWR	310	03/21/1985	12/15/1991
Daya Bay	Unit 1	PWR	984	08/07/1987	08/31/1993
	Unit 2		984	04/07/1988	02/07/1994
Qinshan Phase II	Unit 1	PWR	650	06/02/1996	02/06/2002
	Unit 2		650	04/01/1997	03/11/2004
LingAo	Unit 1	PWR	990	05/15/1997	02/26/2002
	Unit 2		990	11/28/1997	09/14/2002
Qinshan Phase III	Unit 1	CANDU	720	06/08/1998	11/19/2002
	Unit 2		720	09/25/1998	06/12/2003
Tianwan	Unit 1	PWR	1060	10/20/1999	05/12/2006
	Unit 2	(AES-91)	1060	09/20/2000	05/14/2007
Total	11		9,118		

China's future nuclear expansion and spent fuel management

China's nuclear expansion scenarios

In November 2007, China's State Council approved its "Medium- and Long-Term Nuclear Power Development Plan", which set a goal of increasing the nation's nuclear capacity from about 7 GWe to 40 GWe by 2020. In March 2008, the National Development and Reform Commission suggested that the installed nuclear power capacity might even exceed 60 GWe by 2020 due to faster than expected construction. In recent news, China's installed capacity of nuclear power is expected to reach 70 million kW by 2020, 200 million kW by 2030 and 400 million kW by 2050 [8]. As of January 2010, it has 20 units under construction.

One method used to predict China's total electricity installed capacity in 2050 is to multiply its projected population in 2050 by 1 kWe installed capacity per capita, 50% of the current average installed capacity per capita in the OECD countries. Since China's population is predicted to approach 1.5 billion by 2050, the derived projection of total installed capacity by 2050 would be 1,500 GWe [9]. Three nuclear expansion scenarios are presented as possibilities outcomes. The first scenario is the reference case and is based on China's current long-term nuclear power 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 nuclear to have a 30 percent share of installed capacity by 2050 (see Table 2). The third scenario is the low-growth scenario, which anticipates a 10 percent nuclear share by 2050. In the study, the 1 GWe or larger PWRs will still be the mainstream for the next two or three decades.

Table 2. Different growth scenarios assumed up to 2050

Up to 2006	Up to 2020		Up to 2050	
7.8 GWe	The Medium and Long Term Plan Goal	40 GWe	Reference	300 GWe
			High growth	450 GWe
			Low growth	150 GWe
7.8 GWe	The Rapid Growth	60 GWe	Reference	300 GWe
			High growth	450 GWe
			Low growth	150 GWe

Future spent fuel management

Multiple sources show the accumulated spent fuel from operating reactors from 1991 to 2005 is about 1100 tons [10]. Here, the mass of spent fuel unloaded from 2006 to 2020 can be estimated by the annual mass of fuel loaded into one PWR reactor.[1] Table 3 shows estimations of accumulated spent fuel by 2040 for each nuclear growth scenario in Table 2. The new plant designs in China include a 20 year capacity of on-site spent fuel storage. For simplicity in calculations, on-site spent fuel storage space is assumed to be fully occupied before spent fuel needs to be transported to off-site storage facilities. The current nuclear reactor plants have sufficient on-site spent fuel storage capability up to 2020 except for the Daya Bay nuclear reactor plant. Beyond 2020, the current operating plants will gradually run out of space for spent fuel storage. Figure 1 shows the accumulative off-site spent fuel storage space needed from 2003 to 2040. From the figure, by 2017, 500 ton accumulative spent fuel will need to be stored off-site, which will fully occupy the current interim spent fuel pool at the pilot reprocessing site. Beyond that point, additional interim spent fuel space will be needed. By 2040, additional off-site discharged spent fuel will be 3822 tons and 4164 tons respectively for the 40 GWe growth scenario and 60 GWe rapid growth scenario. China could easily use on-site/off-site dry storage facilities or off-site wet storage facilities at the pilot reprocessing site by building another interim spent fuel storage pool with a 3000 tons capacity to accommodate those off-site discharged spent fuel. With such a storage capacity, the spent fuel pools will not be filled up before 2035.

[1] the mass of spent fuel unloaded per year can be estimated by $M = \frac{P \times CF \times 365}{\eta_{th} \times B}$

where, M: mass of 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).In this paper, the installed capacity of 40 or 60Gwe is assumed in 2020;the capacityfactor is 85percent; the thermal efficiency is 33 percent;and the discharge burnup is 50GWd/MTHM

Table 3. Accumulated spent fuel from 1994 to 2040

	1994~2005	2006~2020		2020-2030		2030-2040
Accumulated spent fuel (tons)	**1100**	**Medium and Long Plan (40GWe)**	**5810**	**Reference**	**14730**	**27200**
				High growth	**18771**	**38588**
				Low growth	**10798**	**16119**
		Rapid Growth (60 GWe)	**6579**	**Reference**	**17656**	**29256**
				High growth	**21643**	**40493**
				Low growth	**13668**	**18018**

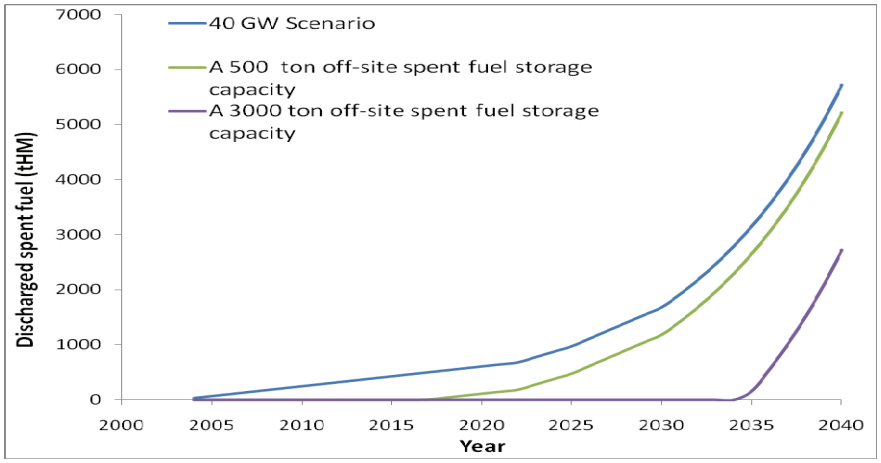

Figure 1. Accumulative additional storage demands with three difference storage scenarios from 2003 to 2040 in China.

China's future nuclear fuel cycling scenarios and analyses

As mentioned before, China plans to apply a closed fuel cycle strategy. China began construction of a multi-purpose reprocessing pilot plant at Lanzhou nuclear complex in July 1997. This project was approved in July 1986. This plant had an initial production capacity of 50 tHM/a, which was later improved to a capacity of 100 tHM/a. In October 2004, the water test of the facility was conducted. This pilot plant should be ready anytime for full-operation now. China started construction of the China Experimental Fast Reactor (CEFR) with a power capacity of 25 MWe (65MWt) in May 2000.It is re-scheduled to have a physics start-up and its first criticality and connect to the grid by 2010.

In this study, different fuel cycling scenarios are developed for the time period between now to the point that the fast neutron reactors are ready to be commercial. Based on the past experience and delays on the construction of China's reprocessing pilot program and the current progress of the commercial reprocessing programs, the commercial reprocessing site will be assumed to operate in 2025. In addition, due to the uncertainty of global fast reactor programs and the past experiences on China's experimental fast reactor (CEFR), the China's demonstration fast reactor (CDFR) will be assumed to operate in 2025 and the commercialization of fast neutron reactors

(CCFR) will not likely happen before 2040. Therefore, in this study, the time period from now to 2040 is of primary focus.

Here, three possible reprocessing scenarios are investigated: 1) without reprocessing and using interim dry storage. All spent fuel will sit in on-site or off-site dry/wet storage facilities; 2) reprocessing as needed to feed its CEFR and CDFRs. China will start reprocessing at 50 tons/year in 2010, then 100 tons/year later. It will reprocess the necessary amount to accommodate the CEFR and CDFR fuel needs The separated plutonium will be used to manufacture MOX fuel to support both CEFR and CDFR program; 3) reprocessing of full scale as much as the capability permits. China will start reprocessing at 50 tons/year in 2010, then increase to 800 tons/year when the commercial reprocessing site is ready. All separated plutonium will be used to manufacture MOX fuel if the commercial MOX manufacturing capability can increase. Table 4 shows key activities and the three scenarios. Table 5 calculates the spent fuel reprocessed and separated plutonium in 2040 based on the three scenarios.

Table 4 Key reprocessing related activities during 2010~2040 and possible spent fuel management scenarios

2010-2020	2020-2030	2030-2040
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) The CDFR constructed (800~900 MWe)	Gen III PWRs/Gen IV The CCFR might be under construction (>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: Start reprocessing 50 tons/year; manufacturing MOX 0.5 tons/year.	reprocessing 50 tons/year and manufacturing MOX fuel 0.5 ton from 2010 to 2024; Start reprocessing 300 tons and manufacturing MOX fuel 8 tons/year [2] for both the CEFR and CDFR after 2025	Continue reprocessing and manufacturing MOX fuel for both the CEFR and CDFR;
Scenario 3: Start reprocessing 50 tons/yr; manufacturing MOX 0.5 tons/year.	Start reprocessing 800 tons/year in 2025; manufacture MOX fuel 40 tons/year in 2025	Continue reprocessing 800 tons/year and manufacturing MOX fuel 40 tons/year

In addition, this section analyzes options to manage the spent fuel taking into account uranium fuel security, costs, and proliferation risks. China argued that as uranium prices increase and uranium resources are depleted, the reprocessing and recycling is the only way to maximize

[2] 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 a 850 MWe power level, a100 GWd/t burn-up rate, a 33% thermal efficiency and a 80% capacity factor.

energy outputs from limited uranium resources, which is a long-term strategy of energy security to China. China's estimated uranium resources around 100,000 tons, which should enable it to satisfy uranium demands for the next decade [11][12]. To meet its long-term needs, it will need to strengthen its domestic uranium exploration and mining capacity. China recently announced that it had verified a large uranium ore deposit in the Inner Mongolia Autonomous Region. And it claims that the amount of newly proven uranium found each year in China outpaces the country's growing demand. Assuming it will be able to mine and process these deposits at a reasonable pace, the group expects to be able to fuel Chinese nuclear power development in the long run [13][14]. In addition, the IAEA's Uranium 2007: Resources, Production and Demand shows that an estimated 5.5 million tons of global uranium resources exist, 130 times the global production of uranium estimated for 2007 [15]. In addition, countries can maintain stockpiles of nuclear fuel with relative ease, given that uranium fuel storage requires far less space than for fossil fuels.

It is understandable world-side that reprocessing and recycling is currently more expensive than once-through cycle with direct disposal of spent fuel and this might be persistent for the next several decades. China's nuclear experts are also aware of this economics. Although economics is not the only basis over the reprocessing policy, it is always one of major factors affecting decisions over reprocessing in other countries [16]. This section will calculate the costs of reprocessing and recycling plutonium for fast reactors associated with the three spent fuel management scenarios given in the previous section based on the newly released economic data from the Idaho National Laboratory (2009) given in Table 5 [17]. In addition, costs of spent fuel reprocessing and MOX manufacturing and interim dry storage of spent fuel are compared in Table 6. The costs of reprocessing and recycling plutonium are much more expensive. It is shown that at the discount rate of 5%, the dry storage without reprocessing and recycling will cost 162.5 million dollars, which only counts 1.5% of the costs under scenario 2 and 0.7% of the costs under scenario 3 respectively. Prior to uranium prices reaching a point where the costs of spent fuel reprocessing and recycling could be economically comparable to direct disposal without reprocessing, interim storage of spent fuel might be a flexible and economic option for now.

Separated plutonium from reprocessing unlike irradiating spent fuel is easily taken and transported. The international security community has concerns about the proliferation risks of plutonium recycling systems. Table 7 shows accumulative separated plutonium under different spent fuel management scenarios. If China starts reprocessing at 800 tons/year in 2025, China's plutonium stockpile will increase to around 190 tons by 2040 before being used in commercial fast reactors. The increasing plutonium stockpile will also increase the cost of safeguards and physical protection. Of course, China could use the plutonium stockpile to manufacture MOX fuel for PWRs. However, if future natural uranium prices cannot increase to the point to make the costs even, using MOX fuel will simply significantly increase fuel cycle costs.

Table 5. Comparison of reprocessing and recycling and storage costs in three studies(2008 U.S.$)

	($/kgHM)
Reprocessing (including waste handling)	2160
MOX fabrication	1950
Dry Storage	120

Table 6. Accumulative costs for three spent fuel management scenarios (2008 U.S. $M)

	0% discount rate	5% discount rate
Scenario 1 (no reprocessing/dry storage)	427.2	162.5
Scenario 2 (reprocessing as needed)	26842.2	10456.8
Scenario 3 (reprocessing at the maximum capacity)	69012.6	25057.5

Table 7. The spent fuel reprocessed and separated plutonium in 2040 based on the three scenarios.

Scenarios	Spent fuel reduced (tons)	Plutonium produced (tons)		Accumulative unused Plutonium (tons)
Scenario 1	0	0		0
Scenario 2	2600	36		0.4*
Scenario 3	13550	40 GW scenario	226.0	192.3*
		60 GW scenario	221.3	187.7*

* Assumed a 25% PuO_2 wt in MOX fuel.

In practice, China's CEFR rescheduled the date to reach criticality in December 2009 and connect to the grid in 2010. In the meanwhile, its reprocessing pilot site will be ready to operate in 2010 as well. Due to China's urgency to manufacture MOX fuel to feed its CEFR, which requires 0.5 ton fuel per year, it is the most likely that China will start reprocessing at the pilot site with an annual capacity of 50 tons in 2010 and manufacture MOX fuel at 0.5 ton/ year soon after when the MOX manufacture pilot facility is ready. China is in the process of negotiating with Russia on the purchase of two BN-800 fast neutron reactors to serve as the CDFRs. If the CDFR purchase is certain, it is very likely China will reprocess more spent fuel to accommodate its CDFRs and CEFR. Due to those facts, reprocessing based on needs would be the best option taking account of economics, non-proliferation and fast reactor technology capability.

Conclusions and Recommendations

This study reviews China's current spent fuel management and explores its future spent fuel generation based on three different nuclear energy expansion scenarios. From spent fuel

generation calculations, China will experience very little pressure to lessen the burden of spent fuel storage in the next three decades. Therefore, spent fuel storage will not be one of major reasons to influence China's decision over reprocessing and recycling programs. In addition, based on the current and near term uranium prices, the foreseeable economics of reprocessing and MOX fuel fabrication technologies are still unattractive currently and the status is unlikely to change in the next several decades. In addition, fissile material management could be a potential challenge. The separated plutonium certainly brings proliferation risks.

Considering China's tremendous energy demands in the future, the current huge commitment on nuclear energy, a complete industrial infrastructure of nuclear science and technology, and China's estimated uranium resources, it is not surprising that China insists on its long-term reprocessing policy and its fast neutron reactor programs. However, the implementation of a closed fuel cycle and fast neutron reactors will also depend on various factors, such as China's technology development, economy, consistent national energy policy, and international cooperation on advanced nuclear technologies. Instead of questioning if China should reprocess or not, China should focus on the questions of when and how China should reprocess taking into account cost, proliferation risks, uranium fuel security, and spent fuel management issues. Therefore, China needs a decision making framework which allows more flexibility and dynamics in order to account for the long timescales inherent in nuclear development. China needs to maintain an economic reprocessing operation to meet the needs of fast reactor R&D activities. In the meanwhile, it should keep active R&D programs on fuel cycle options and technologies to develop a long term solution that is economically competitive with manageable proliferation risks.

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