Economic Aspects of Civilian Reprocessing in China

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ABSTRACT
Currently, China is pursuing a long-term expansion of its nuclear power program and plans to reprocess the resulting civilian spent fuel, recycling the plutonium in MOX fuel for LWRs and in fast breeder reactors. China presently operates three civilian nuclear power reactors, but it plans to build about 20 reactors by 2020. A pilot civilian reprocessing plant has been built at Lanzhou, with a capacity 50 metric tons of spent fuel per year. This plant is ready to start operations now. A key decision now hanging in the balance is whether to proceed with expensive plans to build a larger commercial reprocessing plant, with a capacity of up to 800 tons per year, by 2020. At the same time, China started construction of an experimental fast reactor with a power of 25 MWe in May 2000, and will have to decide whether to build a 300 MWe breeder by 2015, as currently planned. This paper examines whether nuclear reprocessing makes sense for China, taking into account costs, spent fuel management, and proliferation risks. It discusses the status of China's breeder and civilian reprocessing programs, estimates the cumulative of discharged spent fuel and storage capacity in China, and discussion of economics of reprocessing in China. It concludes that China does not urgently need to pursue civilian reprocessing in the foreseeable future. China should instead use interim storage for its spent fuels.

Nuclear Power in China

As a developing country, China's current energy consumption per capita is only half of the world average level and one sixth of the advanced developed countries. It is estimated that the energy consumption per capita in China will need to increase about three times by 2050 to meet its economic growth and to increase living standards. China relies on coal for about 70 percent of its primary commercial energy use. China's vast energy resources lie far from population centers and areas of high energy demand. Increasing China already large consumption of coal would place excessive strains on transportation system and the environment. To address these concerns, China is developing its nuclear power program.[1]

Nuclear power plants. China began its nuclear industry for defense purposes in the 1950s. Since 1979, China's nuclear industry switched its focus to civilian nuclear power. In the mid 1980s, China decided to build nuclear power reactors. China's first commercial plant, Qinshan (a Chinese design 300 MW PWR) went on-line in 1991. In 1994, Daya Bay (two French 900 MW PWRs, went online. Now the three operating PWRs provide 2.1 GW of nuclear capacity, about one percent of total electric power generation. An additional 6.6 GW of capacity is under construction (see table 1), including Qianshan phase two (2X 600 MW PWRs), Qinshan phase three (2X700 MW CANDU), LingAo (2X980 MW PWRs), and Tianwan (2X1000 MW VVERs). These eight reactors will be on line before 2005. After testing a range of reactor types, China is moving to standardization and to self-reliance in design, manufacturing, construction, and operation. China is choosing the 1000 MW-grade PWR unit with 300 MW capacity for each

of the three loops as the main reactor type. China officially hopes to increase its nuclear capacity to 20 GW (about 3-4% of its total electricity generation) by 2010 and 40 GW(about 6% of its total electricity generation) by 2020.[2] However, given that nuclear power is a capital-intensive option,--the cost per KW is more expensive than that of a manufactured coal plant, some projections show nuclear capacity in China falling far behind official goals.[3]

Table 1. China's nuclear power reactors[4]

Nuclear unit	Capacity (MWe)	Type	Design	Construction	Operation
Qinshan I	300	PWR	Chinese	1985.3	1991.12
Daya Bay -1	900	PWR	Franatom	1988.1	1994.2
Daya Bay-2	900	PWR	Franatom	1988.1	1994.5
QinshanII-1	600	PWR	Chinese	1996.6	2002.6
QinshanII-2	600	PWR	Chinese	1996.6	2003.6
LingAo-1	980	PWR	Franatom	1997.5	2002.7
LingAo-2	980	PWR	Franatom	1997.5	2003.3
QinshanIII-1	700	CANDU	CANDU	1998.6	2003.2
QinshanIII-2	700	CANDU	CANDU	1998.6	2003.11
Tianwan-1	1000	VVER	Russian	1999.10	2004.12
Tianwan-2	1000	VVER	Russian	1999.10	2005.12

Closed fuel cycle? Since mid 1980s, China planned to use a closed fuel cycle strategy to reprocess the resulting civilian spent fuel. Like their counterparts elsewhere, Chinese reprocessing proponents argue that China needs to separate plutonium to conserve its limited uranium resources for its growing nuclear power program; to provide energy security; to reduce costs of mining and enrichment of uranium; to reduce the burden of spent fuel at reactor pools, and to increase the safety of nuclear waste disposal.[5] China plans to recycle the plutonium in LWR MOX fuel and fast-neutron breeder reactor fuel. In July 1997 China begun construction of a multi-purpose reprocessing pilot plant (50 tHM/a) at Lanzhou. This plant is ready to start operations now. A key decision now hanging in the balance is whether to proceed with expensive plans to build a larger commercial reprocessing plant (with a capacity of up to 800tHM/a) by 2020 at Lanzhou.

In May 2000,China started construction on the 25 MWe China Experimental Fast Reactor (CEFR). This reactor is located in the China Institute of Atomic Energy (CIAE), about 40km away from Beijing city. It will be in commission around 2005. According to China's fast reactor development strategy, the government is suggested to build a 300 MWe Prototype Fast Breeder Reactor (PFBR) by 2015 and a 1000-1500 MWe Large Fast Breeder Reactor (LFBR) by 2025.[6]

However, the government does not have a formal national long-term development program for the back-end of the nuclear fuel cycle. Although nuclear proponents in China advocate the expansion of the nuclear power and development a plutonium-based fuel cycle, there still is an opportunity for the decision-makers to reconsider China's future nuclear power policy. China's

"nuclear establishment" was restructured in 1998 to reduce government controls on state-owned enterprises to improve their efficiency and make them more responsive to market demands. Consequently, it has been reported that the Chinese nuclear power program has recently slowed down. There is an important opportunity for well-founded comprehensive assessments of the costs, benefits, and risks of these programs, from Chinese experts, to influence the course of the major plutonium decisions now pending in China.

Spent Fuel Management

China's three operating PWRs (one at Qinshan, two at Daya Bay) discharge annually about 60 metric tons of initial heavy metal(tHM) of spent fuel to their reactor pools. By the end of 2000, about 408tHM had accumulated. The spent fuel pools of Daya Bay are expected to be full in 2003-4. The spent fuel will be transferred to the Lanzhou Centralized Wet Storage Facility (CWSF). This storage facility, whose construction started in November 1994, will be ready for operation in 2001-2. It has a capacity of 550tHM. It is expected to add another 550 tHM before 2010. The shipment of spent fuel will begin in 2002 -3. The spent fuel will be reprocessed at Lanzhou reprocessing facility nearby the CWSF. Since most of China's nuclear power plants are within the south and east coastal area, and Lanzhou is in the northwest of China, spent fuel will need to be transported about 3000 to 4000 km. China has been working on spent fuel transport issues.[7] China has some experience in transporting spent fuel discharged from CIAE's HWRR. A feasibility study on the transport of spent fuel from Daya Bay plant has been completed. This feasibility study concluded that a combined transport option by both sea and rail would be preferable. Another option would be by road.

Spent fuel generation. Like other countries, reprocessing proponents argue that China needs to reprocess partly in order to reduce the burden of increasing spent fuel. To examine this issue, here I will discuss China's spent fuel generation and spent fuel storage capacity in the future. As a reference scenario, the projections of spent fuel generation are based on the following assumptions: 1) China's installed nuclear capacity by 2005 will be in Table 1. After that, to estimate conservatively the accumulation of spent fuel, the government projections for nuclear installation of 20GW by 2010 and 40GW by 2020 will be used; and will be assumed to increase linearly the number of PWRs in each period with a combination of 600MW and 1000MW PWRs; 2) After 2010, all PWRs (except Qinshan I) will increase their burn-up to 43,000MWd/tHM; 3) The capacity factor of the reactors is 80%; 4) Except Daya Bay reactors(10 years AR pool storage capacity), AR pools of all new reactors will have 15 years storage capacity; 5) All reactor life time will be 40 years (except 30 years for Qinshan I). Consequently, the projection of cumulative inventory of spent fuel generation in China is shown in Table 2.

Table 2. Cumulative spent fuel generation in China (1992—2020) (a reference scenario)

Type	2000(tHM)	2005(tHM)	2010(tHM)	2015(tHM)	2020(tHM)
PWR	408	942	2508	4695	7051
CANDU	0	440	1056	1936	2640
Total	408	1382	3564	6901	9691

Addition spent fuel storage demands. Based on the above reference scenario assumption, additional spent fuel storage requirements for PWRs are estimated (see figure 1). In the case of PWR's spent fuel, China will need 408tHM additional storage capacity by 2010. The current operational Lanzhou storage facility (550 tHM) will be able to meet such requirements. By 2020, the addition storage requirement will be about 1026tHM. If Lanzhou storage facility receives another 550tHM of capacity around 2010 as currently planned, there should be no spent fuel storage issues. By 2030, the additional storage requirements are about 4300 tHM. If China wants to expand its Lanzhou storage facility, it should be easy to do so because the facility is built in a modular mode. Alternatively, by that time China could build a less costly dry storage facility.
For the case of CANDU spent fuel, it is estimated that the AR pools will be full around 2017.By 2020 , it will need about 350 tHM additional storage. It should not be a big concern to build a storage facility to receive spent fuel from CANDU reactors--most likely, only for Qinshan's two CANDUs. In any case, China is not planning to reprocess CANDU spent fuel.

In practice, China is likely to have less installed nuclear capacity than the reference scenario, thus the spent fuel inventory is likely to lower than projected in the reference scenario. Also, China could take other measures to delay the requirements for additional storage, such as re-racking of spent fuel at already-built reactor pools, building larger pools for new reactors, inter-shipping spent fuels between pools at the same or nearby NPP sites. In short, given the existing and planned Lanzhou storage capacity, China should not be concerned about the burden of spent fuel storage at least until 2020.

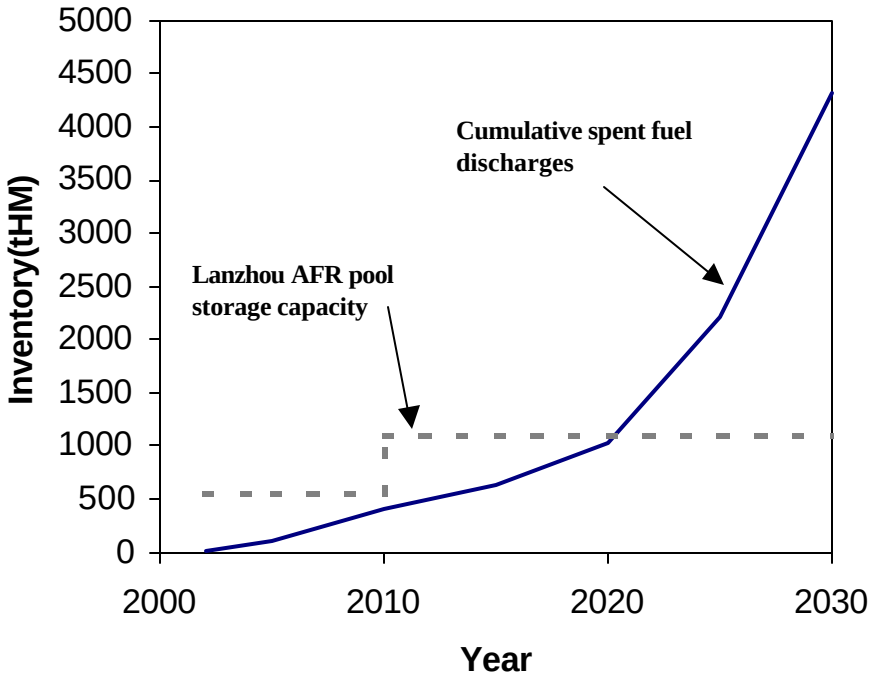

Fig.1 Cumulative additional storage demands at China's PWRs
(Reference scenario)

Economics of Plutonium

At present, China has no commercial reprocessing plants and MOX -fueled reactors. However, the Chinese nuclear industry is advocating that China should pursue civilian plutonium reprocessing to supply its FBR and fuel its PWRs with MOX. Besides the proposed FBR program, building a MOX fuel demonstration facility is currently under consideration. While China is focusing on economic development, the cost of plutonium recycling should be an important factor in the long-running debate over the approaches to the management of spent nuclear fuel and the nuclear fuel cycle. As a newcomer to nuclear power, it is the time for China to optimize its fuel-cycle choice to minimize costs and risks while maximizing flexibility and options for the future. It is increasingly being realized world-wide that reprocessing plutonium and recycling it, as breeder or MOX fuel, is more expensive than a once-through cycle with direct disposal of spent fuel. Most likely, this situation will not change in the next several decades, does it make sense for China to pursue plutonium reprocessing?

As a case study, I explain here a comparison of costs of reprocessing for MOX fuel fabrication with direct disposal of spent fuel. Based on the projection of China's spent fuel generation, China needs no additional storage by 2020. Moreover, even if China plans to reprocess its spent fuel, it would have to wait until 2020. Thus, we consider the period 2020-2030. After 2020,China would have three options for its spent fuel: reprocessing, direct disposal and interim storage. It is assumed that 1) reprocessing for MOX route: after 2020, additional PWR spent fuels are reprocessed for PWR MOX fuels; After production, the vitrified high-level waste (VHLW) will be stored for 25 years prior to final disposal (i.e., about 40 years after the spent fuel discharged from reactors. China proposes to dispose of VHLW around 2050 at a prospecting site within Northwest). 2) direct disposal route: after the spent fuel is transferred from their AR pools, they are stored for 25 years before the disposal.

Consequently, the comparison of costs of reprocessing and direct disposal is given in table 3. It is shown that, at discount rate of 5%, the direct disposal option would be 70% cheaper than reprocessing for MOX fuels under this scenario. In the analysis, the current average value for the unit price of uranium purchases, reprocessing, MOX fabrication, etc. are used. However, even across a wide range of different assumptions concerning the specific prices for reprocessing and MOX fabrication services, uranium prices would have to increase several times for reprocessing to be economically comparable. For example, even if MOX fabrication prices were $500/kgHM (far below current contract prices) and the reprocessing price were only $500/kgHM (far bellow the long term sustainable price for reprocessing), the breakeven uranium price (at which both options are comparable) is still over $200/kgU (roughly six times the current uranium purchase price). This is very unlikely in the foreseeable future.[8] In the case where terrestrial uranium resources become scarce, the huge amount of uranium (4500MtU) in the oceans , is expected to be recoverable in the range of $80-100/kgU. [9] This would be likely to keep plutonium reprocessing and recycling uneconomic compared with direct disposal for many centuries.

Similarly, the costs of recycling plutonium in breeders using current technology, which is dependent on the capital cost of breeders (generally much higher than that of LWR) and cost of fabricating and reprocessing breeder fuel and the like, would be even much higher than that of

the direct disposal option. Thus, from an economic perspective, it is not rational for China to pursue plutonium reprocessing and recycling.

Table 3. Comparison of additional cumulative costs for reprocessing vs. direct disposal through 2030 for PWR spent fuels (2000 U.S.$M)

Options	0% discount rate	5%
Reprocessing for MOX		
Transport	161.5	45
Reprocessing	3230	900
MOX fuel fabrication[a]	237.1	66
VHLW disposal	613.7	50.5
Total	4242.3	1061.5
Direct disposal		
Storage/transport	807.5	225
Disposal	1098.2	90.3
Total	1905.7	315.5

Assumed unit prices: Uranium Purchase ($kgU)=33; Conversion ($/kgU)=6; Enrichment ($/SWU)=100; Fabrication ($/kgSWU)=250; Transport($/kgHM)=50;Storage(($/kgHM)=200; Reprocessing ($/kgHM)=1000;VHLW disposal l($/kgHM)= 190; SP disposal ($/kgHM)= 340; MOX fabrication ($/kgHM)=1500.
Source: Matthew Bunn, Steve Fetter, and John Holdren, The Economics of Reprocessing versus Direct Disposal of Spent Fuel (Cambridge, MA: Belfer Center for Science and International Affairs, Harvard University, forthcoming).

Note: [a] in calculating the MOX fuel fabrication cost, MOX fuel credit was considered.

Discussion

While China should experience little pressure to lessen the burden of spent fuel generation in next two decades and the economics argue against a civilian reprocessing program, other factors such as the environmental impact, energy security, and proliferation risks should also influence Chinese government decision-makers' long term policy on nuclear fuel cycle. In the case of environment impacts, recent concerns have been raised in Britain and France over the health impacts of reprocessing in the region surrounding the reprocessing plants. Now it is believed that plutonium reprocessing and recycling will increase workers' and public radiation exposures and increase accident risk, while not significantly reducing the burdens of radioactive-waste management. In addition, it will generate additional categories of waste that increase the waste-management burden.[10]

One major motivation for reprocessing advocates in China is energy security. They argue the nuclear energy will reduce China's energy dependence on foreign energy sources such as oil. However, nuclear energy would play a very limited roles in such issues. For example, even based on the high projection of China's nuclear capacity by 2020, nuclear energy will account for only 2% of total primary energy demand which is not a big deal for energy security. If China's energy system becomes much more dependent on nuclear energy and world-wide

uranium resources are to be used up soon, nuclear energy security could become an important concern. However, this is not likely. Indeed, China could use up its own currently-proven uranium resources within a few decades under its current proposed nuclear program. However, nuclear energy security would depend on world-wide uranium markets instead of domestic uranium resources, as shown by some countries, including South Korea, that do not have their own uranium production, but still develop their nuclear power plants. It is estimated that by 2100, the world cumulative uranium consumption could be about 20 MtU. The world uranium resource is estimated at 50-125MtU, recoverable at costs of less that $130/kgU. About twice as much uranium would be recoverable at price of $260/kgU.[11] If the uranium in the oceans is taken account, it will support the power reactors with once-through cycles for many centuries. Moreover, uranium suppliers in the world market are diverse geographically and politically, and unlikely to collude to raise prices or limit supplies. In case uranium security becomes a concern, for example, a "strategic" reserve of uranium fuel would be inexpensive to buy and easy to store, this would be a much less expensive strategy then reprocessing.[12]

As far as international security is concerned, the separation of plutonium will increase the risk of theft by proliferant states and subnational groups. Moreover, once China processes its spent fuels, separated civilian plutonium will soon exceed its small military plutonium stockpiles. For example, the pools of Daya Bay PWRs (which discharge annually about 50 tHM spent fuel) will be full around 2003-2004. If Lanzhou pilot reprocessing plant (50 tHM/a) reprocesses this spent fuel, the separated plutonium will surpass China's military plutonium stockpile (reportedly about 2 tonne) within five years. Thus, it will increase the cost and burden of safeguards and physical protection. Apart from its impacts within China, China's civilian reprocessing policy could have important influence on the international community. For example, the civil use of plutonium in one country can serve as encouragement or excuse for its use in other countries, which will increase nuclear proliferation. Conversely, if China does not develop civilian reprocessing, this could set a good example for other countries that are contemplating reprocessing.

In conclusion, based on this analysis China does not need to pursue a reprocessing program in the foreseeable future. While it seems clear that direct disposal is cheaper than reprocessing, China has no plans for direct disposal. While the debates on permanent options for management and disposal of spent fuel and nuclear waste are still continuing world-wide, it would be highly desirable for China to choose an interim storage option instead of pursuing a reprocessing program. From the perspective of economics, utilities can save substantial sums by postponing near-term spent fuel management costs to the long term[13], thereby leaving all options open and leaving time for technology to develop further and choices to become clearer. A recent study further shows that "interim storage of spent fuel offers a safe, flexible, and cost-effective near term approach to spent fuel management that may be attractive regardless of a particular country's perspective on the continuing debate over whether spent fuel should ultimately be reprocessed or disposed of as waste".[14] Thus, an interim storage approach would give China a substantial opportunity to carefully develop a long-term policy for the nuclear fuel cycle.

Reference

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[9] Bunn, et al., *The Economics of Reprocessing versus Direct Disposal of Spent Fuel*.

[10] John Holdren, "Energy and Environmental Issues in the 21st Century and the Future of Nuclear Power", Presentation at the Tokyo University-Harvard University symposium on the Future of Nuclear Energy, 22 July 2000, Tokai, Japan.

[11] Bunn, et al., *The Economics of Reprocessing versus Direct Disposal of Spent Fuel*.

[12] Jungmin Kang and Harold Feiveson, "South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing," *The Nonproliferation Review*, Vol.8, No.1, 2001.

[13] It is shown that that postponing the cost of either option, and allowing costs to be discounted into the future, is highly desirable. For example, at a discount rate of 5%, a reprocessing cost of 1000/kgHM need only be postponed for five years to save over 200/kgHM—the central estimate of the cost for providing dry cask interim storage. Moreover, the interim storage in dry casks can be continued for decades at a very little operational cost(For more details see Bunn, et al., *The Economics of Reprocessing versus Direct Disposal of Spent Fuel*).

[14] See recent report: Matthew Bunn, et al., *Interim Storage of Spent Nuclear Fuel—A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management*, A joint report from the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy, June, 2001.