Options for China's nuclear spent fuel management

Hui Zhang
Managing the Atom Project
Kennedy School of Government, Harvard University
79 JFK St., Cambridge, MA 02138, USA

Presentation at

Workshop on Strategic Nuclear Issues in East Asia, Beijing, China, March 5-6, 2014

Options for spent fuel management

---Direct disposal (once-through cycle)

--permanent storage ,e.g. the deep geological repository

--US YM project canceled

---Reprocessing (closed fuel cycle)

--use MOX fuel for LWR or FBR

---Export spent fuel to other countries

--for storage or reprocessing

--HLW would back to the exporting country

---Interim storage (up to 100yrs) , a wait-and-see approach

Factors affecting spent fuel policy

---Economics

---Energy security /uranium resource

---Storage capacity

---Environmental aspects/waste management

---Security and nuclear proliferation

---Technological and political culture

China's nuclear energy development

-- 50s defense nuclear—1979 focus switched to civilian nuclear power--mid 80s decided to develop NPP

--by January 2014, operating 17 reactors of 15 GWe (less 2% electricity), 31 reactors (34G) under construction.

--since 2004, China's policy of nuclear development changed from " moderate development" to " energetic development"

--After Fukushima Event (March 11,2011),the State Council announced17 March 2011:

China would suspend approval of all new nuclear power stations; conduct comprehensive safety checks on all existing plants; review all nuclear projects including those under construction.

--Oct.2012 : Medium- and Long-term Nuclear Power Development Plan (2011-2020)

- A return to normal construction at a controlled and orderly pace.
- Permission for a limited number of new nuclear power reactors to be built in coastal sites that have been comprehensively evaluated.
- A ban on new inland nuclear power projects, because the government fears a shortage of cooling water should accidents occur at such plants.
- A requirement that all new projects meet the safety standards of the world's most advanced nuclear reactors, known as third generation or Gen III reactors. Compared to earlier technology, these new designs incorporate improved fuel technology, superior thermal efficiency, passive rather than active safety systems, and standardized designs aimed at reducing maintenance and capital costs.

-- Now: 2015: 40 GWe; 2020: 58 We.

Operating power reactors in China by 2013

Reactors	Capacity(Mwe)	Type	Design	Operation
Qinshan I #1	320	PWR	China	1991
Daya Bay #1	984	PWR	Franatom	1994
Daya Bay #2	984	PWR	Franatom	1994
Qinshan II #1	650	PWR	China	2002
Qinshan II #2	650	PWR	China	2004
Lingao #1	990	PWR	Franatom	2002
Lingao #2	990	PWR	Franatom	2003
Qinshan III #1	728	Candu	Candu	2002
Qinshan III #2	728	Candu	Candu	2003
Tianwan #1	1060	VVER	Russia	2007
Tianwan #1	1060	VVER	Russia	2007
Lingao #3	1080	PWR	China	2010
Qinshan II #3	650	PWR	China	2010
Qinshan II #4	650	PWR	China	2011
Lingao #4	1080	PWR	China	2011
Hongyanhe I #1	1080	PWR	China	2013
Ningde I #1	1080	PWR	China	2013

China's plans on reprocessing

In the mid 1980s, China selected a closed fuel cycle strategy to reprocess spent fuel and has recently speed up development of this strategy.

Motivations

---Full use of uranium resources; Reducing cost of mining, milling and enrichment uranium

---Provide MOX fuel ; Development of FBR;

---Energy security concerns;

---Reduce the waste repository volume

---minimizing radioactive toxicity, disposal of radwast safely;

---Reducing the burden of spent fuel at reactor pools

The reprocessing pilot plant

--Capacity: 50 tHM/year; Jiuquan nuclear complex, Gansu;

--Project approved July 1986; construction commenced July 1997; first reception of spent fuel from Daya bay reactors in Sept. 2003 , water test conducted Oct.2004.

--Successful hot test Dec 21 2010, operating about 10 days, producing 13.8kg Pu. Since then, suspending.

--Capital cost : about 2.2 billion RMB in 2009 ($ 323 million),$6500/kg ; several times more than earlier estimates.

--Long delay: from projected approval to hot test =14 year, then operating only 10 days.

China's commercial reprocessing plans

--CNNC negotiating with Areva, Capacity: up to 800 tHM/year

--Recently CNNC proposes a domestic plant: 200 tHM/year

--Preliminary work started (site selection, etc) ; commission by 2025?

--In addition: A pilot MOX fuel fabrication (0.5t/a) building. A commercial MOX fuel fabrication plant planned in commission by 2025?

China's Fast Reactor Programs

--- Chinese nuclear experts believe: To install 240 GWe of nuclear power (15-20%) by 2050, China had to develop FBR, it is impossible to use only PWRs because of the limitation of uranium resources.

--- China's nuclear energy roadmap (three stages):

PWR---FBR---Fusion reactor

--FBR programs listed in National Hi-Tech "863 program" in 1986

---China Experimental Fast Reactor (CEFR) operating in 2010.

--Larger commercial FBRs to be commissioning 2030-2035.

China FBR Development Strategy (suggested by CIAE, Xu Mi, 2009)

Reactor	Power (MWe)	Design beginning	Commission
CEFR (I)	20	1990	2010
CDFR (II)	600-900	2007	2018-2020
CCFR (II)	Nx 800-900	2015	2030
CDFBR (III)	1000-1500	2018	2028
CCFBR (III)	1000-1500	2020	2030-2032

Status of China Experimental Fast Reactor

--Conceptual design: 1990-92

--CEFR project approved in 1995

--Preliminary design 1996-97

--detail design 1998-2003

--construction start: 2000.5

--reactor building completed 2002.8

--physics start-up & first criticality: 2010.7

Location	**35km from Beijng**
Floor surface of building	**43731 m^2**
Main building size	**78m x 68m x 57m**
Water supply	**4500 ton/day**
Power supply	**3000 kw**
Thermal power	**65 MW**
Electric power	**20 MW**
Plant life	**30 yrs**

Spent fuels management

---given the current capacity of Jiuquan AFR pool(550tHM) and planning for expanded 1300 tHM and potential larger pools,

---China will have little pressure to reduce the burden of NSF storage issue.

Offsite storage space (tons)	Estimate of when the storage will reach full capacity
500	2017
1000	2025
3000	2035

Discussion:

In practice, China could take measures to delay requirement for additional storage: e.g.

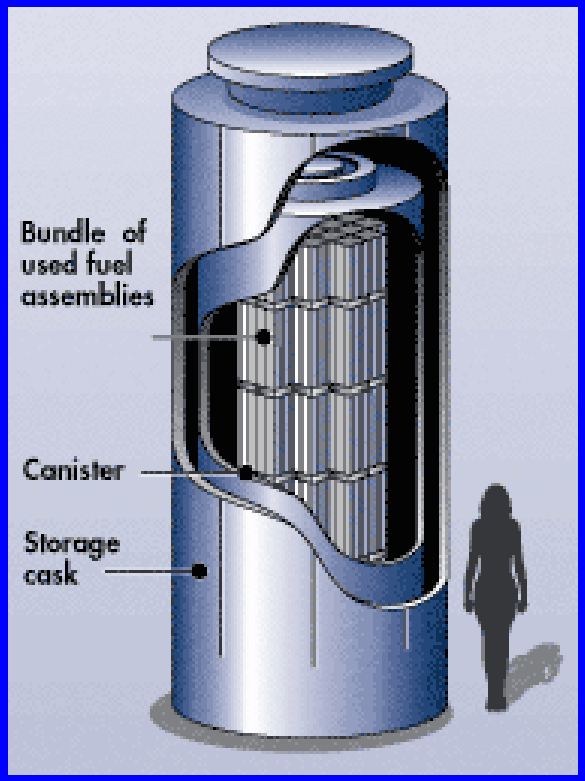
#re-racking spent fuel at already-built reactor's pool;

#building larger pools for new reactors;

#inter-ship spent fuels between pools at the same NPP site.

#on-site dry cask storage.

Dry cask storage



diverse technologies available
cheaper ($100-200/kgU)
safe storage for decades
for 75% of global nuclear capacity

See more: e.g.
Bunn, et al., Interim Storage of Spent Nuclear Fuel—A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management (Harvard Univ.& Univ.of Tokyo,2001.)

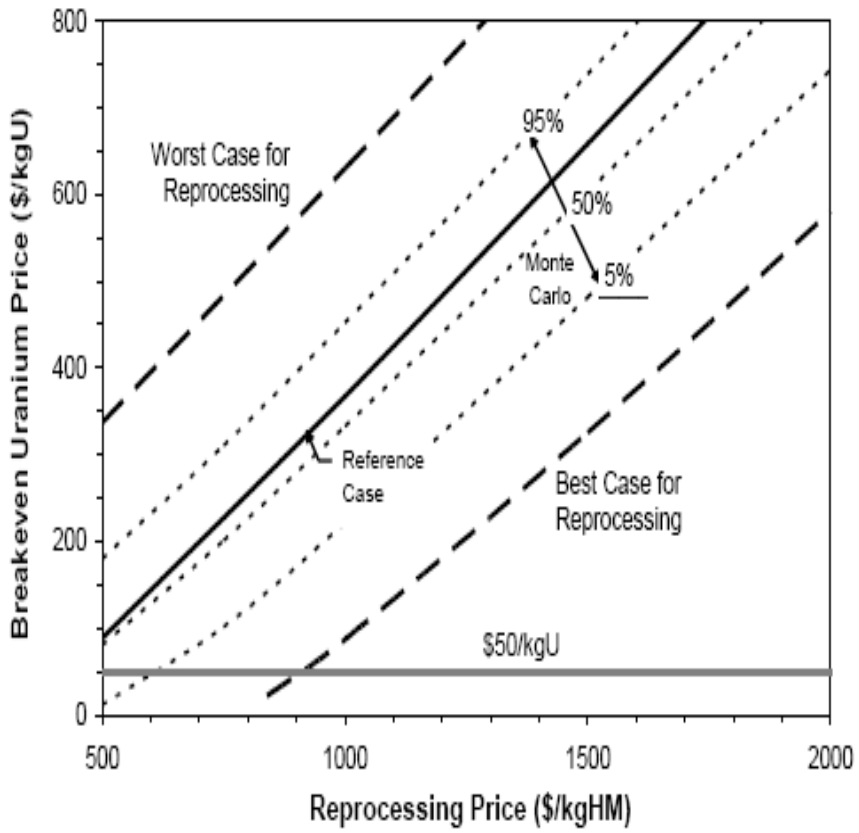
Economic aspects of nuclear reprocessing

--Many scientists show that reprocessing" option is much more expensive that direct disposal option

--e.g Harvard group concluded :
"reprocessing and recycling plutonium in existing light-water reactors (LWRs) will be more expensive than direct disposal of spent fuel until the uranium price reaches over $360 per kilogram of uranium kgU)…"

"Reprocessing and recycling plutonium in fast-neutron reactors (FRs) with an additional capital cost, …will not be economically competitive with a once-through cycle in LWRs until the price of uranium reaches some $340/kgU."

Figure 2.1. Breakeven uranium price as a function of the cost of reprocessing, for various sets of assumptions about the cost of other fuel-cycle services.



Bunn et al., Harvard 2003

La Hague reprocessing plant

---2000 tU/year

---$18 billion overnight capital and $0.9 billion/year operational cost

--$1000-3000/kgU with and without 10% capital charge

Reprocessing can double the cost of the fuel cycle

Source: Frank von Hippel,2010

Economic Forecast Study of the Nuclear Power Option, (Report to the Prime Minister of France: 2000)

Reprocessing:	100%*	67%	27%	0%
Back end costs	$84 B	$74 B	$61B	$41B
Front end savings	$-10 B	$-8 B	$-2B	0
Net costs	$74B	$66B	$59B	$41B

•Derived scenario.
Source: Frank von Hippel,2010

---Turning LEU spent fuel into MOX spent fuel will increase cost of nuclear power in France by $33 billion over 45 years
---Reprocessing would be justified economically in France at $600/kgU.

Japan Rokkasho (800 tU/yr capacity)

---planned to be completed by 1985

---actually completed in 2006

---not operating by 2013, ready in 2014?

---$20 billion investment, $1.5 billion operation cost per year

---$4000/kgU

Comparing the levelized cost of electricity (LCOE) for different fuel cycles (An MIT study: 2009)

Fuel cycle	LCOE (mill/kwh)	Increased
OTC	75.32	--
LWR MOX	76.99	2.2%
FR: burner	77.39	3%
FR: Breeder	78.51	4%

Note: e.g. 2-4% increase meaning :for 10 GWe installation, $1-2 billion /yr more than OTC.

Plutonium recycle in FBR?

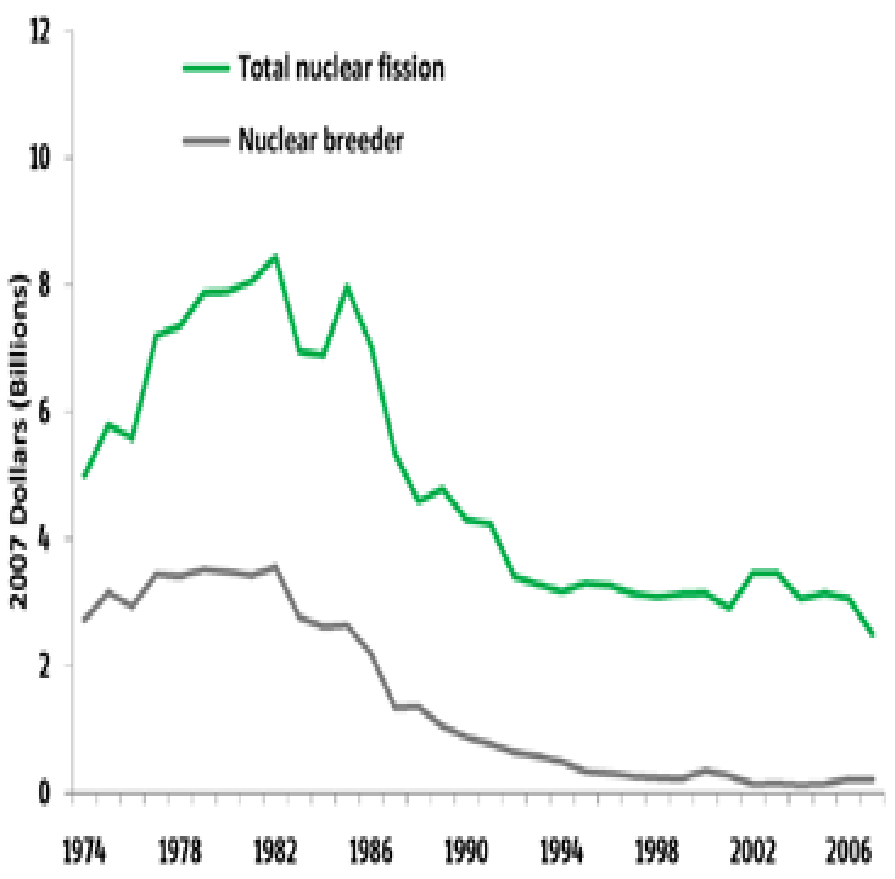
-- Only a few FBRs operating, less 1GWe

--Only commercialized FBR—Superphenix shutdown in 1998 and in decommissioning

---No commercialized FBR now

---R&D in OECD declined

---Many scientists doubt about those key assumptions of the rational for pursuing FBR



Total fission and breeder R&D and demonstration funding in the OECD (1974-2007)
Source: Fast Breeder Reactor Programs: History and Status, IPFM Feb.2010.

Major experimental, pilot and demonstration FBR

	MWe	MWt	operation		MWe	MWt	opeartion
China				**Russia**			
CDFR	20	65	**2010--**	BN-350(kazak)	350		1972-99
France				BN-600	600		**1980-**
Rapsodie		40	1977-83	BN-800	800		2014?
Phenix	250		1973-2009	**UK**			
Superphenix	1240		1985-98	DFR	15		1959-77
India				PFR	250		1974-94
FBTR		40	**1985-**	**USA**			
PFBR	500		2014?	EBR-I	0.2		1951-63
Japan				EBR-II	20		1963-94
Joyo		140	1977-	Fermi 1	66		1963-72
Monju	12		1994-95 2010--	Fast Flux Test facility		400	1980-93
				SEFOR		20	1969-72

Source: Fast Breeder Reactor Programs: History and Status

Energy security consideration

---one major motivation for Pu reprocessing and recycling is "saving uranium" to increase "independent" supply of uranium.

---the key for nuclear "Energy Security"—world uranium resource

If energy system depends much more on Nuclear and U resource soon used up---nuclear energy security would be important, UNFORTUNATLY, not such case.

China's uranium resource

---CAEA 2007: 100 kt of uranium resource (<$130kg/U)

---"Red book" 2011: about 220 kt (two times more than 2007)

---Based on recent report 2013, China would have a huge potential of U resource. E.g. could 2 million ton deposited.

---China's U resource supply " enough for near-term; secure for mid-term; big potential in the future"

China's demand for natural uranium

---For the rapid growth (60GWe), by 2020 China could use around 1/3 known uranium resource(220 ktU) .
---however, China's reactors using 1/3 fuel from domestic resource ,others from oversea. If keep this mode, China's own uranium would supple for next 20 yrs.

China actively accesses to oversea uranium

---In 2006, the China National Nuclear Oversea Uranium Resource Development Company (NNOURD) set up—a deal with Australia: 20,000 t of uranium /yr.
---also a deal with Canada in 2004: access to Canada's uranium mine.
---NNOURD claimed to secure over 200,000 t uranium reserves in Africa, Australia, Canada, and Central Asia.
---CGNPC: also invested to ensure its nuclear fuel supplies.

China's exploration and investment in Domestic and oversea uranium resource should not constrain China's development of nuclear energy for next several decades.

New MIT Study (2010): The future of the Nuclear Fuel Cycle

Finding:

---There is no shortage of uranium that might constrain future commitments to build new nuclear plants for much of this century…

Recommendation:

---An international program should be established to enhance understanding and provide higher confidence in estimates of uranium costs versus cumulative uranium production

Uranium needs

---2 to 4% of the cost of nuclear electricity

---Uranium prices have small impacts on electricity prices

---Best estimate of 50% increase in uranium cost if:

- ***Nuclear power grows by a factor of 10 worldwide***
- ***Each reactor operates for a century***

World wide uranium supply

---total world uranium resources are dynamic and related to commodity prices.

Higher price—more exploitation—more resource.

---Moreover, 4500MtU in the oceans, could be extracted at significant high price (say, e.g. +300)---thus it will support the power reactors with once-through cycles for many centuries.

Stockpiling strategies for China:

---e.g. import and store three months oil =could buy NU supplying 40 GWe PWRs for 25 years.

Tails recovery:

---e.g. for Xp=5%: decreasing tails 0.3 to 0.1%: reducing NU 30%; Need to balance SWU cost, but still cheaper than MOX case.

Reserve domestic U resource,

---while investigating domestic U resource, but can mainly use foreign resource first.

Waste volume considerations

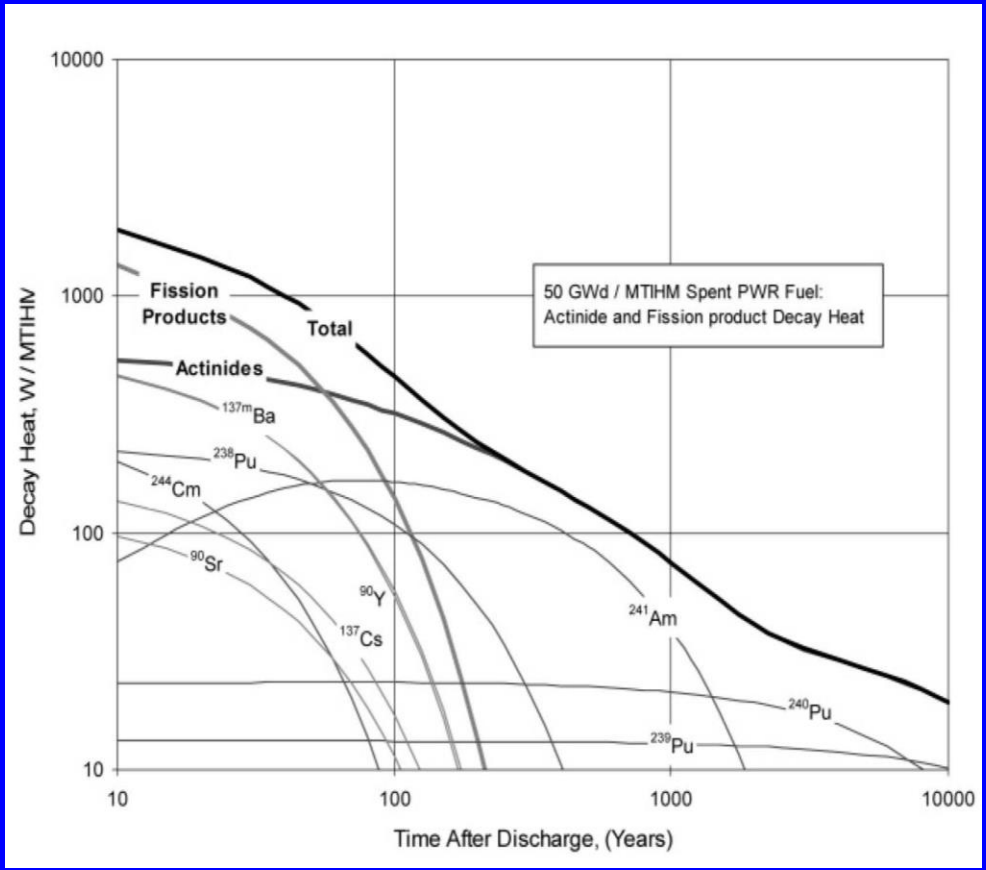
- **The loading of YM-like repository is constrained By the temperature limits (due to the high decay heat from SF) not by the physical volume).**

The temperature limits:

--- Peak rock temperature midway between adjacent drifts must remain below the local boiling point (96 C

—to allow water to drain through the repository at all time

---Peak rock temperature at drift walls must remain below 200 ºC to keep structural integrity of the Repository.

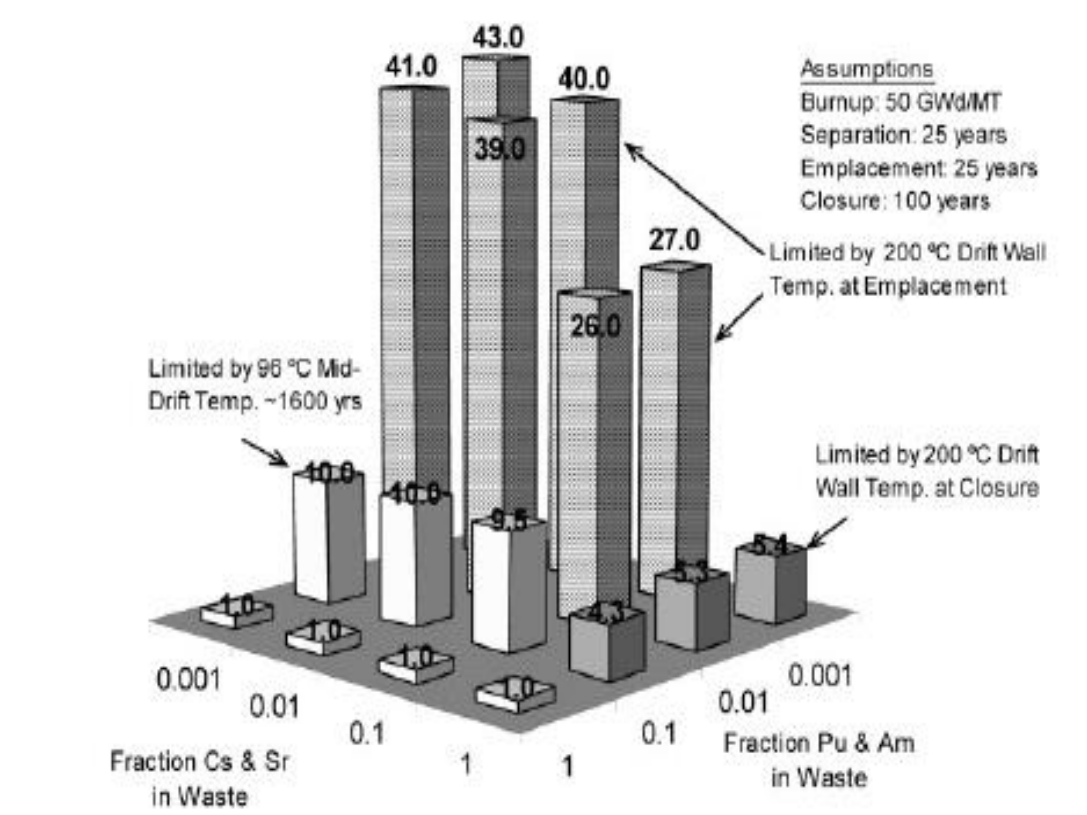


Contributions to decay heat from a spent fuel as a function of time

---For regular reprocessing: increasing the drift loading—a factor of 5.

---For Mox case: very small benefit, only a factor of 1.087.

---If 99.9% Pu, Am, Np removed & 99.9% Cs, Sr and dtrs removed: a factor above 40.



R. Wigeland,et al., NuclearTechnology,vol.154 (April2006)

- **Under all scenarios, a location is required for geological disposal of HWL. The question is whether such space is limited in China .**

---One major motivation for US reprocessing and recycling (under Advanced Fuel Cycle Initiative or GNEP) was: potential increase in utilization of space in a geologic repository like YM (due to the legislated limitation of the loading for YM is 70,000 t and too difficult to get a second site).

---However, China should not have such a limit. In fact, China's Beishan area could have a huge capacity, and maybe more sites (if needed).

Nuclear proliferation

- Reactor-grade plutonium is weapon usable; reprocessing—separated Pu easy taken, unlike SF "self-protecting" —nuclear proliferation

- Civilian Pu stocks will soon exceeds its small military Pu stocks-- increase cost and burden of safeguards and physical protection
  e.g. reprocessing of 800 tHM/yr---8 t separated Pu/yr, much higher than WgPu in stocks.
- Could affect other non-weapon states concerning reprocessing—provide cover for proliferation
- China concerns about Japan's Pu, China's own reprocessing would make it difficult to dissuade others.
- If no reprocessing, would set up an good example for other countries

Nuclear Security Concerns

--it is far easier for insiders to steal small amounts of material over time without anyone noticing at bulk processing facilities (reprocessing, enrichment, fabrication).

-- In nearly every case in which authorities have seized stolen HEU or separated plutonium the material has been in bulk form, such as powder, apparently stolen without detection by insiders from bulk processing facilities.

---China pilot reprocessing plant: MUF higher

---insider is more difficult to prevent

See details: Hui Zhang, "Securing China's Weapon-Usable Nuclear Materials." *Science & Global Security* no.1 (Feb 18, 2014): 50-71.

Conclusions

- To examine whether China should build a large commercial reprocessing plant and fast-neutron reactors in the near term, it should take account the costs, energy security, proliferation risks, nuclear security, health and environmental risks, and spent fuel managements issues.

- Other countries experience shows that plutonium recycle is much more costly, much less safe and secure than LWR once-through cycle. China would not make an exception.

Recommendations and discussions (cont'd)

- Known resources of low-cost uranium worldwide are sufficient for this century. China can invest more in improving estimates of U resource, taking strategy for oversea exploitation, word trade , uranium stockpiling.

- Before the cost and risks of reprocessing and fast breeder technologies are reduced, China should take an interim storage approach--This interim storage option will give China a substantial opportunity to carefully develop a long-term policy for the nuclear fuel cycle.