Thoughts on China's Nuclear Reprocessing Policy

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China's nuclear power target and policies for expansion

-- As of March 2017, 36 reactors in operation (33 GWe) , 21 reactors under construction (23 GWe)

-- The new 13th Five-year Plan reaffirms: 58 GWe in operation and 30 GWe under construction by 2020 .

-- May 2016 NEA : working on details on Nuclear power development of 13th FYP (draft)—plans 120-150 GWe by 2030.

-- Some recommend that China install a nuclear power capacity around 250-400 GWe by 2050.

-- Within a few decades, China is expected to operate more nuclear power plants than any other country in the world.

Main Drivers-- Addressing Air Pollution

- China is the world's largest producer and consumer of coal. Coal has dominated China's energy mix for decades – causing heavy air pollution problems.
- In 2012, two thirds of China's cities could not meet the country's own air-quality standards. Based on a study, over 99% of China's 500 largest cities did not meet the World Health Organization's air-quality standards.
- Chinese Academy of Environmental Planning estimated the cost of environmental degradation to $230 billion in 2010 or 3.5% of the nation's gross domestic product – threefold increase since 2004.

-- The 12th Five-Year Plan for Energy Development (released 2013), plans to increase non-fossil fuel energy use to 15 percent of the energy mix by 2020

-- In 2014, China's non-fossil energy accounted for 11.2 % (Hydro 8%, Nuclear 1.2%, and Renewables 2%). However, Coal supplied the majority (66%) with Oil (18%) and Gas (5%).

Main Drivers – Reducing Carbon Emission

- **As a result of high coal consumption, China has overtaken the United States as the world's leading energy-related CO2 emitter each year since 2006. China is unsurprisingly facing domestic and international pressure to act on its emissions.**

- **In November 2014, U.S. President Barack Obama and Chinese President Xi Jinping stood together in Beijing to make a joint announcement, in which China pledged to increase the share of non-fossil fuels in primary energy consumption to about 20% by 2030.**

- **June 2015, China submitted UN its Intended Nationally Determined Contribution (INDC): peaking its carbon emissions by 2030 or earlier; lowering carbon emissions per unit of GDP by 60% to 65% from the 2005 level; increasing the share of non-fossil fuels in the primary energy mix to about 20%.**

- **Xi Jinping reaffirmed those pledges at the 2015 global climate change conference in Paris.**

- **To reach these goals, Chinese leaders see a massive increase in nuclear power as a necessity. Nuclear power of 130 GWe by 2030 would account for about 5% of total energy use and would constitute just one quarter of the non-fossil energy needed.**

Main Drivers – Promoting Energy Security

- **To increase national energy security through diversifying prime energy supply, thereby reducing concerns about energy resource limitations, and uneven distribution of energy resources.**

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;

--Successful hot test Dec 21, 2010, operating about 10 days, producing 13.8kg Pu. Later: 25.4 kg

--problem: much higher MUF ; high waste volume.

--Capital cost : about 3.2 billion RMB in 2014; several times more than earlier estimates.

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

--Resume operation recently

200 tHM/yr reprocessing plant

- To provide plutonium for initial demonstration fast-neutron reactors
- Approval in July 2015, site preparation at Jinta, Gansu
- Operational 2020?

800 tHM/yr reprocessing plant

- Since 2007 negotiation with AREVA – disputes over price, conditions
- Finished first stage (technical) and second stage (business) since 2015
- Since Summer 2015, pre-selection sites at east costal areas
- CNNC plans to start construction 2020

China's fast neutron reactor projects

China's experimental fast reactor

--Construction started May 2000
--Completed in July 2010
--Design capacity: 25 Mwe
--Located: CIAE, Beijing

--Operations:

- 1st criticality 7/2010, 40% power;
- 26 hours in 2011,
- no operation 2012 &13;
- 72 hours Dec. 2014 (100% power)
- since then for R&D

CFR-600 demonstration fast reactor

-- design power: 600 MWe
--location: Xiapu, Fujian province
--Dec. 2015, Concept design;
--by end 2016, preliminary design
--to start construction in 2017
--commission in 2023.

Commercial fast reactor

--a 1000 MWe CFR-1000 in 2030s.

Others

--to buy Russian BN-800?

Spent fuels off-site storage

#Jiuquan Spent Fuel Wet Storage Pool at the pilot reprocessing plant

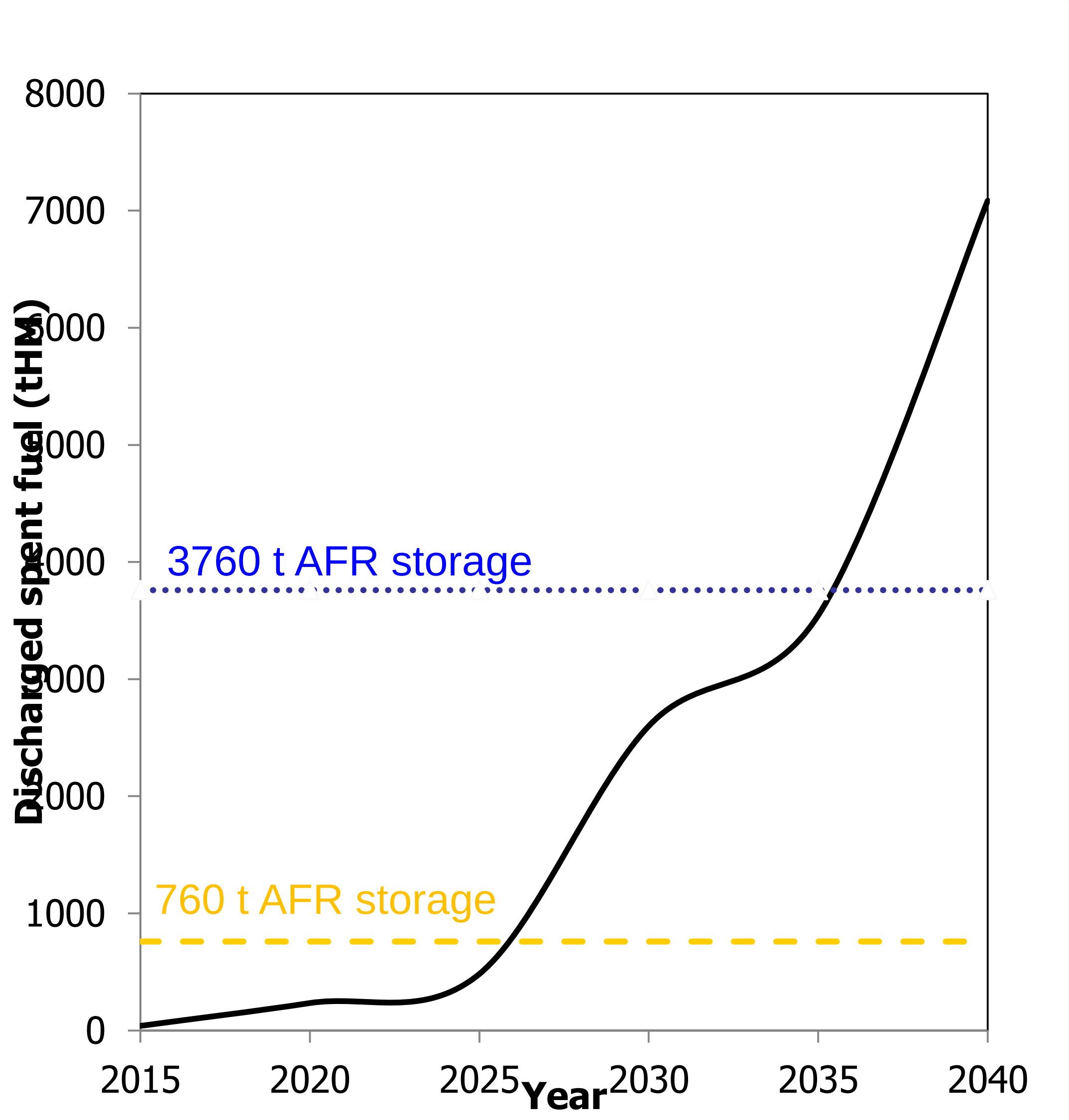
--Capacity:550tHM , started reception of SF in 2003; full around 2015.

--Additional capacity of 760 tHM ready to work (full around 2027).

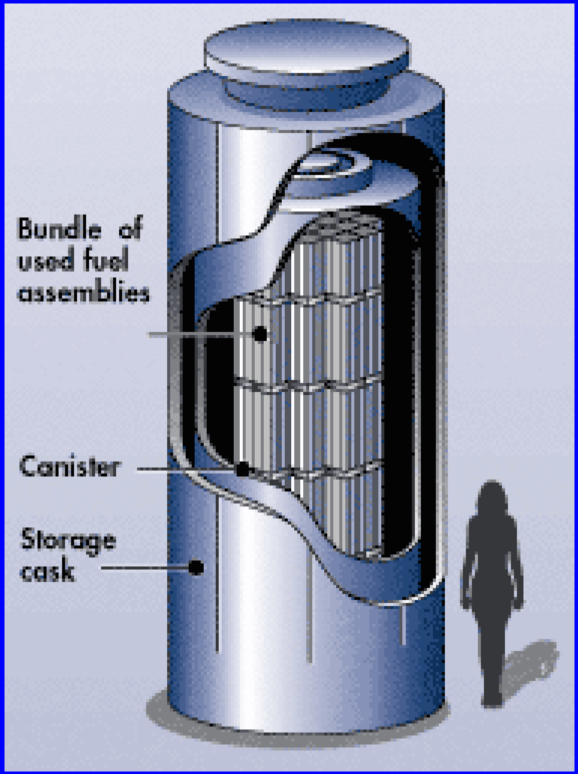
--If additional 3000 tHM added after 2027--full around 2035

#In Summary

---Given the current capacity of planning for expanded and potential larger pools, China will have little pressure to reduce the burden of NSF storage issue.



Cumulative additional storage demands beyond storage in reactor pools from 2015-2040



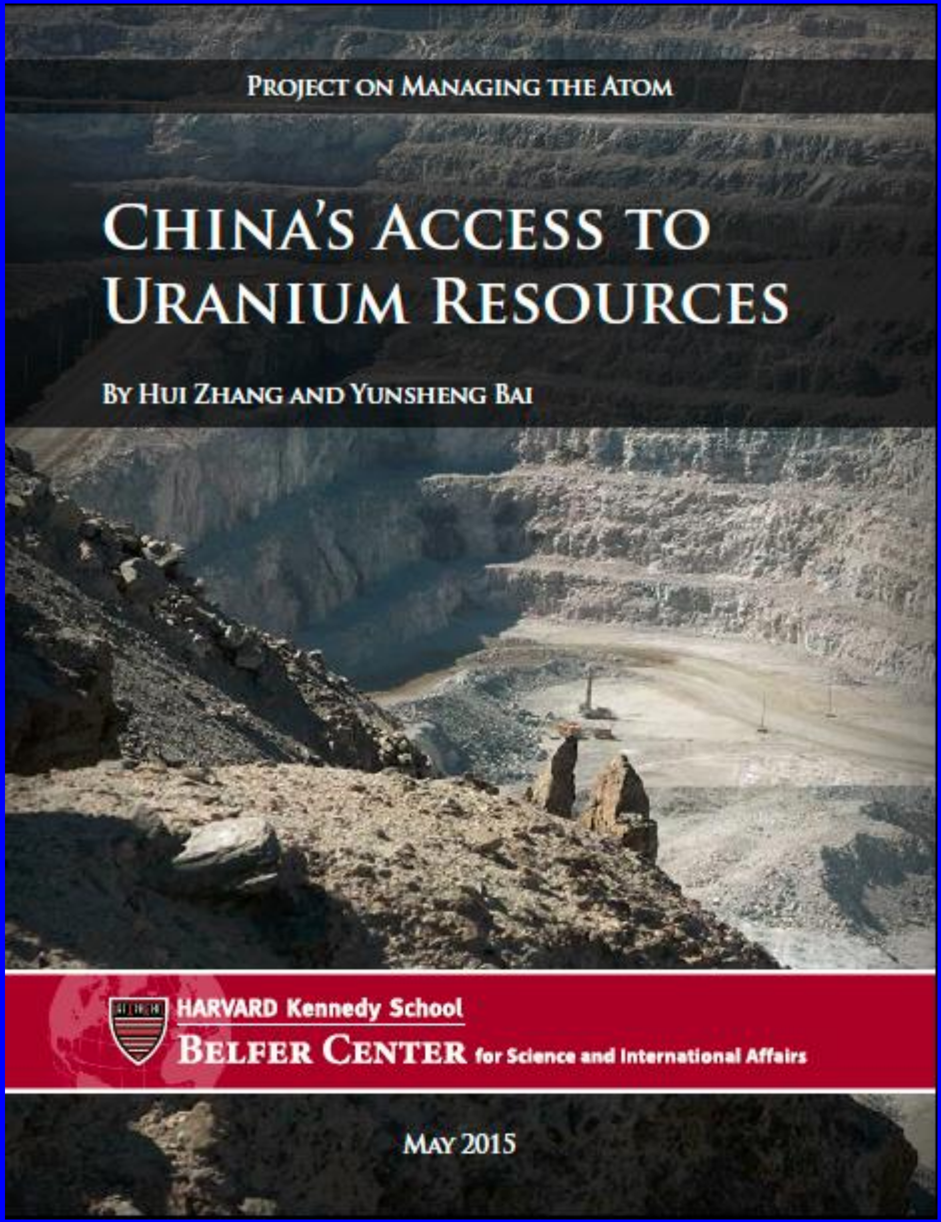
Dry cask storage

diverse technologies available
cheaper ($100-200/kgU)
safe storage for decades

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.)

Should China's Uranium Resources Constrain Its Nuclear Power Development?

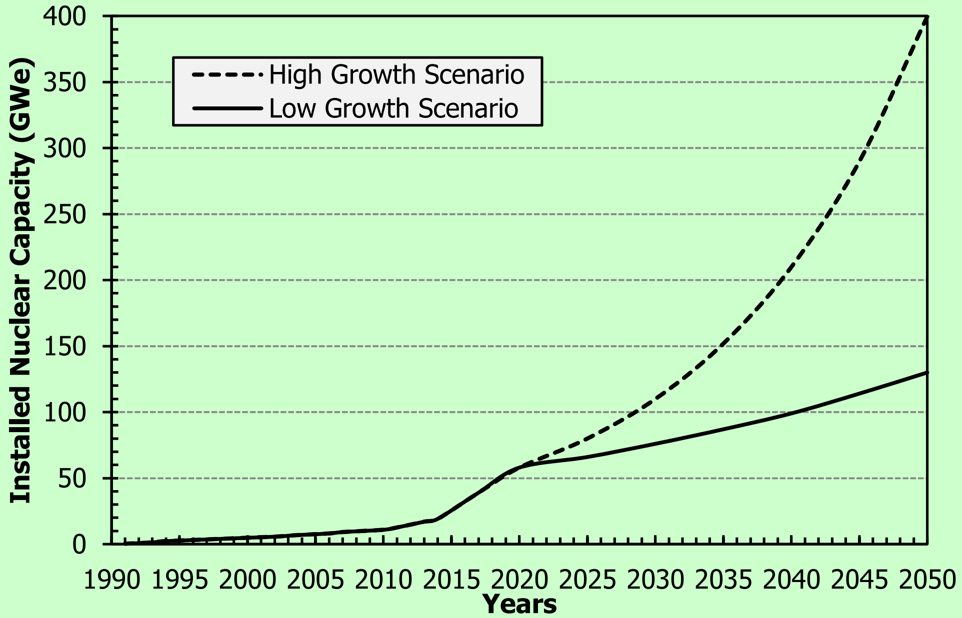
--A new Harvard report concludes :uranium supply enough for 2050, even under the most ambitious scenarios.



China's Growing Nuclear Power

- **High-growth scenario: 20 GWe (2014) – 58 GWe (2020)-- 400 GWe (2050)**
- **Low-growth scenario: 20 GWe (2014) – 58 GWe(2020)-- 130 GWe (2050)**

Projected nuclear generation capacity (GWe) for two scenarios



Projection for China's Cumulative Uranium Demand (2014-2050) (NU: kt)

	2014	2020	2025	2030	2035	2040	2045	2050
Low Growth Scenario	5	53	101	160	225	296	384	479
High Growth Scenario	5	53	111	191	301	454	663	952

China’s Known Uranium Resources

(*In situ* and recoverable resources as of January 1, 2013, tonnes of Uranium)

	<USD 40/kgU	<USD 80/kgU	<USD 130/kgU	<USD 260/kgU
RAR: In situ/recoverable	69000/51800	125000/93800	160000/120000	NA/120000
IR: In situ/recoverable	18500/13900	73000/54800	105500/79100	NA/79100
Identified resources: In situ/recoverable	87500/65700	198000/148600	265500/199100	NA/199100

China’s uranium potential

Based on uranium metallogeny, new models, and exploration data from the past several decades, recent predictions ---over 2 Mt potential uranium resources.

Major reasons, e.g.

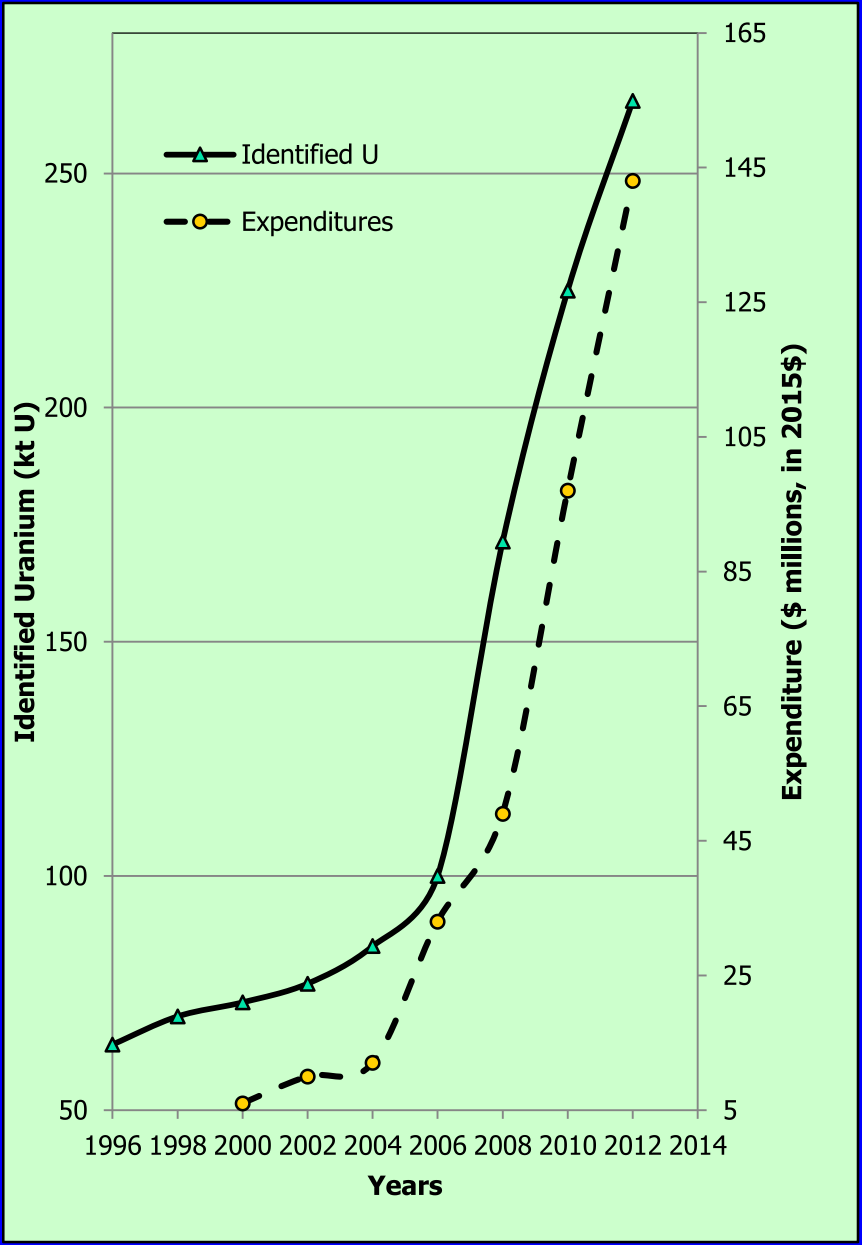
--About 2/3 area very low levels of exploration, or untouched

--A big resource potential could lie at a greater depth.

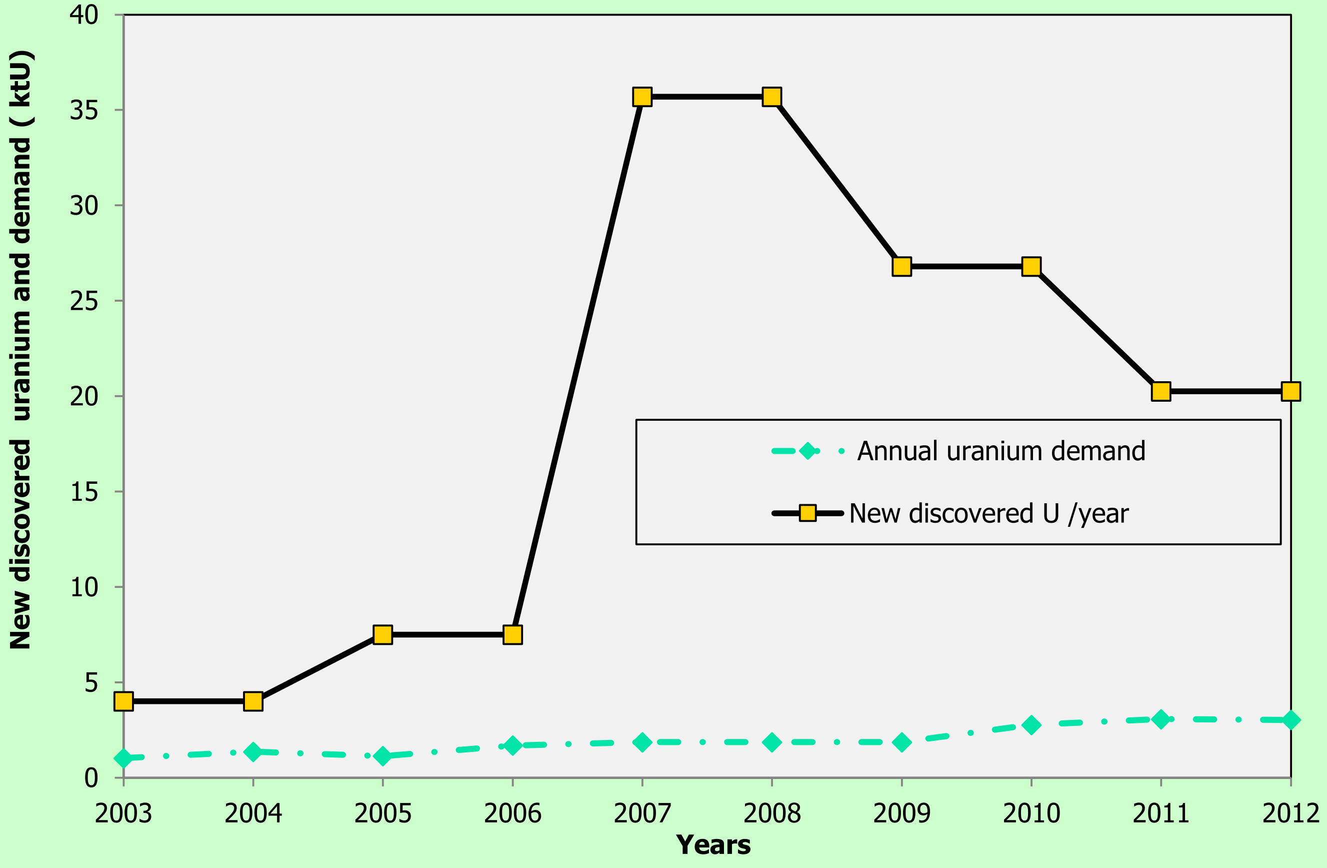
--Favorable geological conditions for uranium mineralization: East China on the uranium metallogenic belt of the Pacific Rim; North China on the Eurasian uranium metallogenic belt.

China's identified uranium resources increased rapidly as exploration expenditures increased from 2004.

The known uranium resource--a dynamic economic concept. Depend on a number of factors, including technological advances, engineering feasibility, exploration expenditures, uranium prices, and limitations of ore grade.



China's new discovered uranium resources per year is much more than its annual uranium demand



Chinese Overseas Uranium Investment

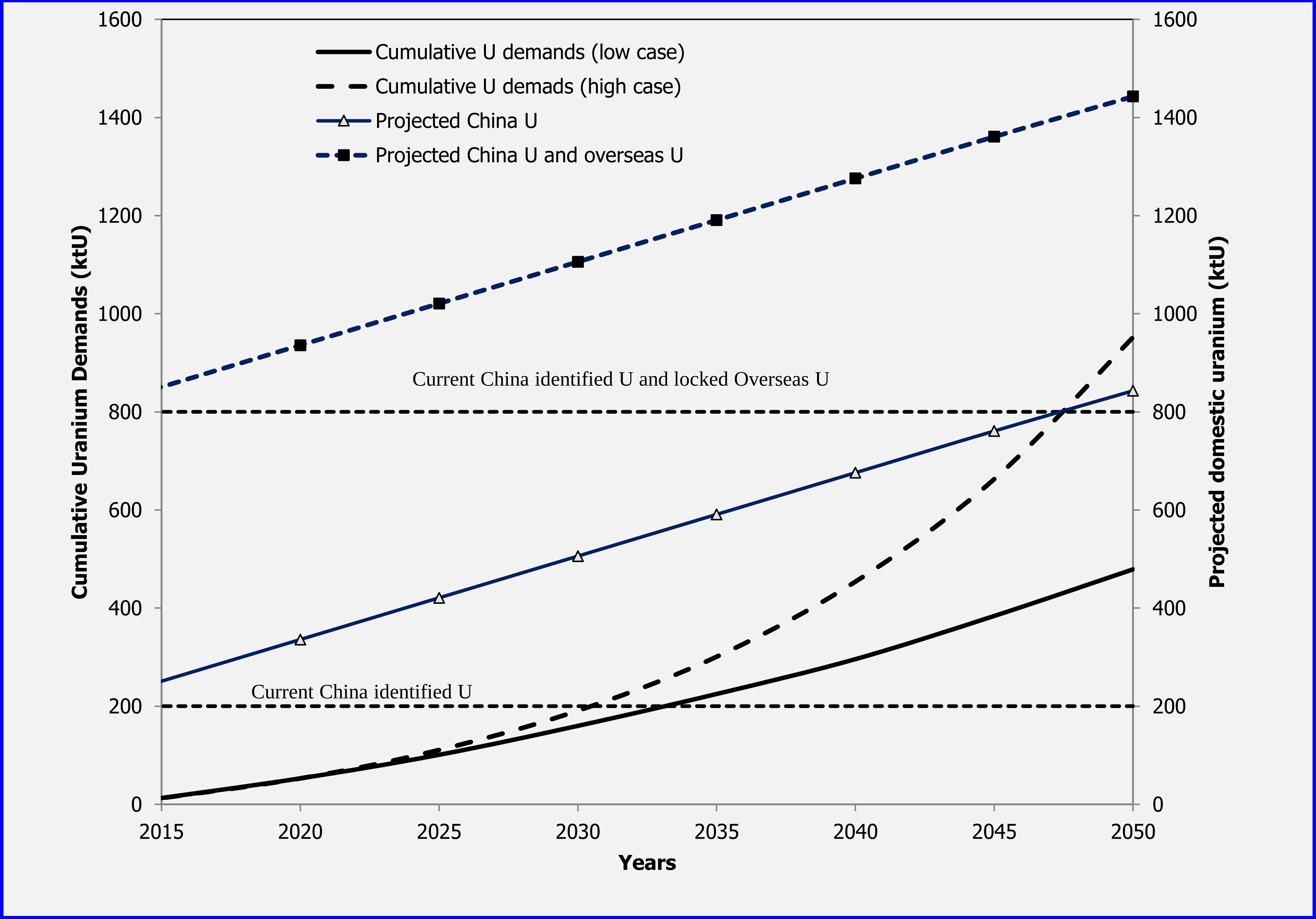
-- China will discover more resources, but a majority of the uranium ore discovered in China is of poor quality and will be costly to mine in comparison to that in other countries.

-- Since mid-2000s, pursuing "Three One-Thirds" rule—one third from domestic supply, one third from mining abroad, and another third from direct international trade.

A summary of China's pursuit of uranium overseas

Items	Possible recovered uranium resources for China (ktU)
Traded uranium	132
LEU deals	38
Surplus (existing inventory)	60
CNNC mining	160 (198 ktU of in situ resources, recovery rate of 80%)
CGN	250 (307 ktU in situ resources, recovery rate of 80%)
Others (SinoSteel, etc.)	NA
Total	632 (three times known domestic resources)

China's projected cumulative uranium demand



Security of World Uranium Supply

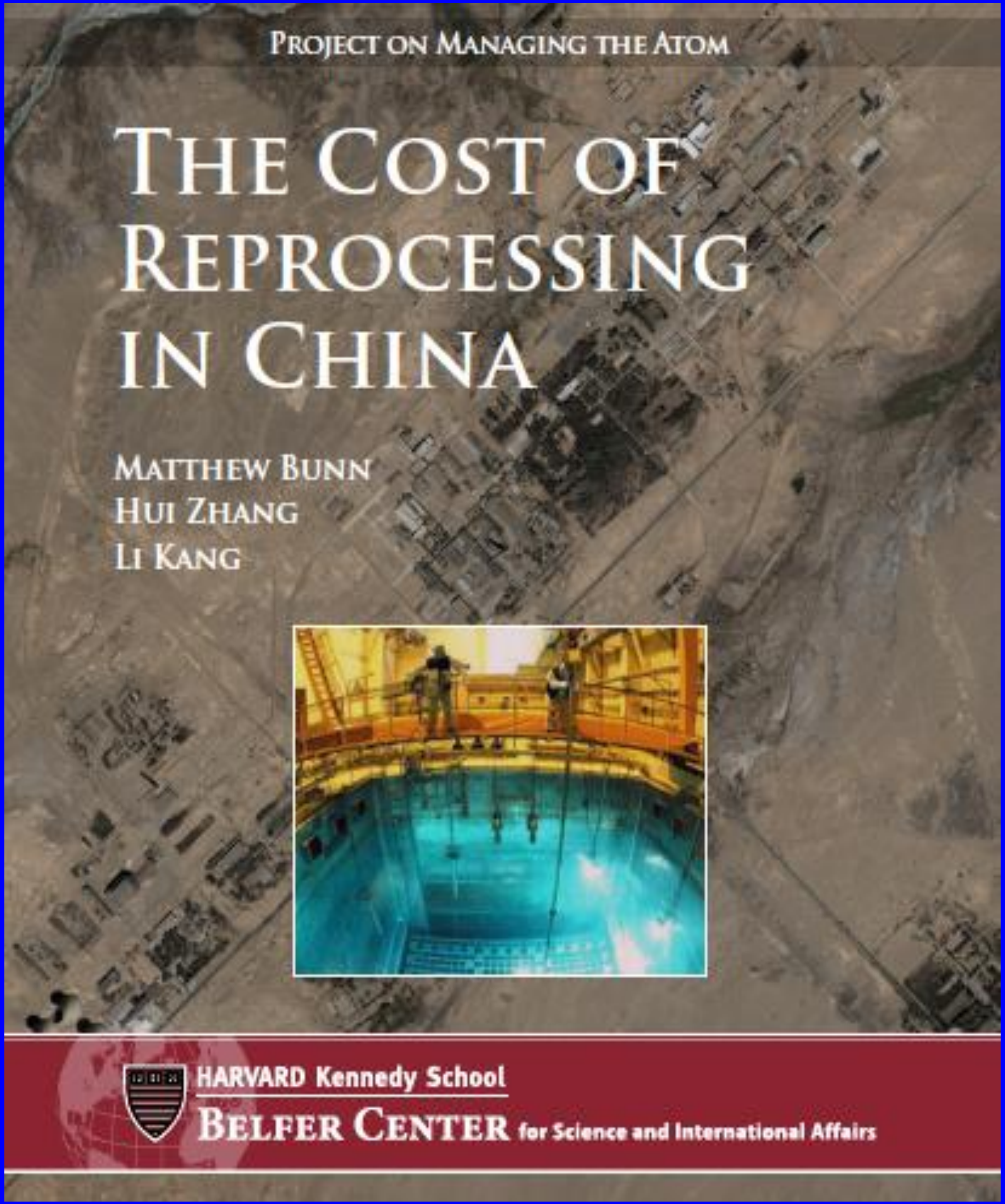
- **World uranium resources are diverse both geographically and politically, and collusion to raise prices and/or limit supplies would be unlikely.**
- **The global distribution of uranium resources and nuclear power capacity is highly suited to trade complementarity: those states with the most nuclear power generally have less uranium, and those states that have the most uranium generally don't have that much nuclear power. The trade in uranium resources, therefore, naturally takes place in a global market place.**

--Global identified uranium resources have more than doubled since 1975, in line with increasing expenditure on uranium exploration, even as over 2 MtU has been used.

--Uranium resources likely enough to supply global nuclear power growth in this century.

---A new report on the cost of China's reprocessing 2016

---China could save many billions by storing spent fuel rather than reprocessing it



http://belfercenter.ksg.harvard.edu/publication/26158/

The capital cost estimates--extrapolated from the pilot plant

- **200 tHM/yr reprocessing plant**
  - Rule of thumb for engineering cost extrapolation: the ratio of costs is equal to the ratio of capacities raised to an exponential scaling factor:

$$C/C0=(M/M_0)^{\gamma}$$

  - 4x scale-up from design capacity of pilot plant; for 4x scale-up CNNC experts assume γ=0.9
  - Hence cost goes from $910M for pilot plant to $3.2B

- **800 tHM/yr reprocessing plant**
  - CNNC experts assume γ=0.85 for this larger scale-up
  - Hence capital cost would be $9.6B
  - Far lower than reported € 20B French offer for 800 tHM integrated reprocessing/MOX fabrication plant

- **But expect real costs could be higher**

Cost for reprocessing & dry cask storage: high and low estimates

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

Even without financing costs :

---Even low estimate for 800 tHM/yr plant operated at full capacity throughout 40-year life--save over $20B by dry casks for that period

-->$9B savings for low estimate of 200 tHM/yr plant

Per-kilogram reprocessing costs: high and low estimates: 800 tHM/yr plant

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

Full fuel-cycle costs

Case 1: LEU direct disposal vs. recycling as MOX

--Even under favorable assumptions for reprocessing (e.g. low estimate costs for 800 tHM/yr plant and MOX), reprocessing increases fuel-cycle costs by 2/3 ($2.46 $/MW-hr to $4.16/MW-hr)

Case 2: LEU direct disposal vs. breeders

-- Under the same favorable assumptions for reprocessing, and assuming breeders only 20% more expensive to build, thus total electricity cost for the breeder case increases about 20%.

- **In both cases, for reprocessing to be economic, U would have to rise to ~$450/kgU.**

China's geological disposal project

--China plans to bury HLW (vitrified HLW and some spent fuel) underground at a depth 500 -1000 m.

--The design requirement : the repository be large enough to store all high level wastes produced by China during the next one to two hundred years.

--The plan includes three stages:

- 2006-2020: establishment of an underground laboratory and selection of one or two candidate repository sites ;
- 2021-2040 :selection of final repository site ;
- 2040-2050 : construction of the repository .

--The Beishan area (near Jiuquan) in Gansu , underlain by granite, has been selected as the primary candidate site, over 11 deep boreholes have been drilled.

Repository volume-reduction benefits?

--Some argue: reprocessing to reduce HLW volume by 95% (because FP is 5% of SP mass)

--In practice, the FP mass not determine the ultimate volume of disposal wastes, neither the volume required for a deep geological repository.

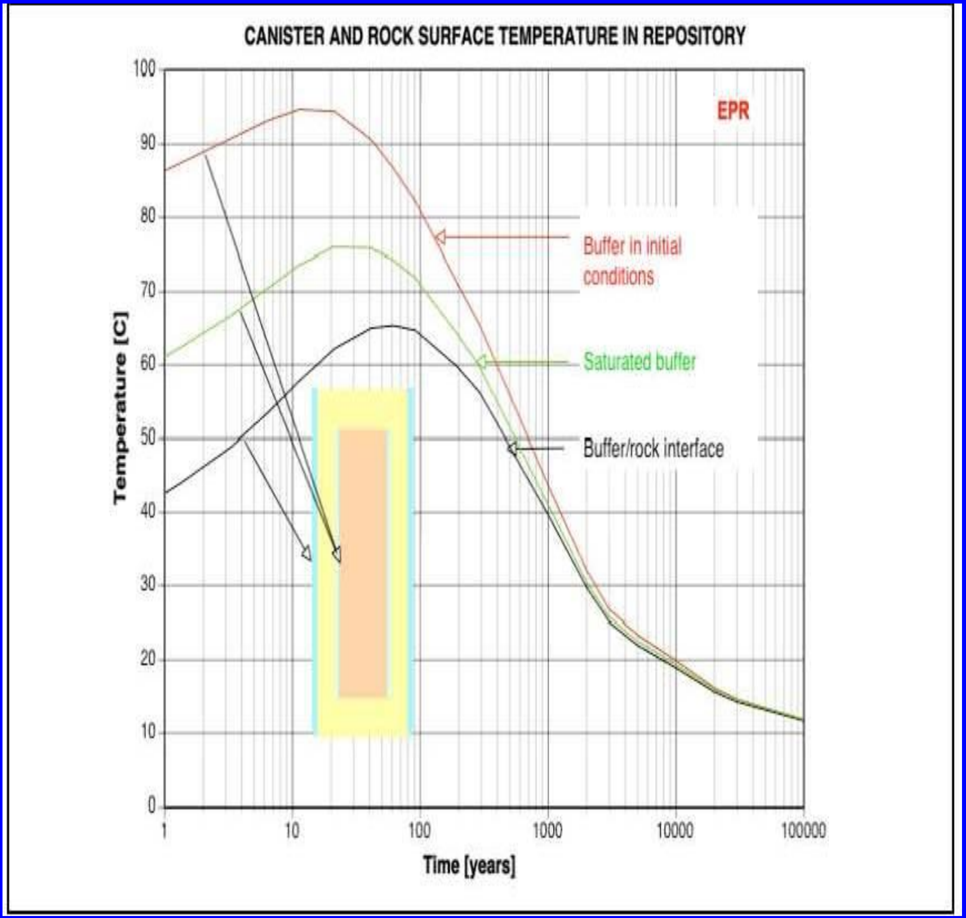
--E.g.: Careful calculations for the France case show: if include all the radioactive waste streams from reprocessing and MOX fuel fabrication that require deep burial, the volume of a geological repository would be same as the original low-enriched uranium spent fuel. ---See: Mycle Schneider and Yves Marignac, Spent fuel reprocessing in France, International Panel on Fissile Materials, 2008.

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

- **The Beishan repository would have basically the same design as Finland's Olkiluoto spent fuel repository in which spent fuel would be buried in copper canisters surrounded by bentonite clay in granite.**

- **The loading capacity of Olkiluoto-like repository would be determined by the need to keep the temperature of the bentonite below 100 ^{o}C. For 50-year spent fuel with average burn-up of 50 MWd/kgU, the maximum temperature would occur about 15 years after emplacement.**

- **Assuming all of the transuranics could be separated from the nuclear waste stream, the loading capacity of the repository would go up by approximately a factor of two—which could also be achieved by waiting until the spent fuel is one hundred years old before burying it!**



Kari Ikonen and Heikki Raiko, Thermal Dimensioning of Olkiluoto Repository for Spent Fuel,Working Report 2012-56.

Dose reductions or increases?

--Some argue that the risks surrounding leakage in geological repositories could be reduced if all the long-lived isotopes of plutonium and other transuranics contained in spent fuel were transmuted (or fissioned), thus significantly reducing the doses of radioactivity that could escape due to any leakage.

--But studies show that long-lived fission and activation products in spent fuel—not isotopes that could be fissioned through breeders and reprocessing—dominate the radioactivity doses that leakage could release.

--A new study addresses: "Because of the radioactive releases from reprocessing plants, it is quite possible that there would be a net dose increase from reprocessing and transmutation as a result of routine releases of radioactive gases and possible accidental releases from liquid high-level waste processing and stores." see: Frank von Hippel, Chapter of "Transmutation" in "Plutonium Separation in Nuclear Power Programs: Status, Problems, and Prospects of Civilian Reprocessing Around the World," IPFM Report, July 2015.

--The US National Academy of Sciences concluded in 1996 , based on a review of the costs and benefits of reprocessing and fast neutron reactor programs, that :

"none of the dose reductions seem large enough to warrant the expense and additional operational risk of transmutation."--Nuclear Wastes: Technologies for Separations and Transmutation, National Academy Press, 1996,

Nuclear proliferation concerns

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

- China's civilian Pu stocks will soon exceeds its small military Pu stocks-- increase cost and burden of nuclear security and safeguards.
- Could affect other non-weapon states concerning reprocessing—providing cover for proliferation.
- China concerns about Japan's Pu programs, China's own reprocessing would make it difficult to dissuade others.
- If no reprocessing, would set up an good example for other countries.

The nuclear security risks of reprocessing

- Even the pilot plant has shown some challenges to establish an effective MC&A system: e.g. a larger MUF.
- Would be even more difficult to establish an effective MC&A system at a larger plant than at the much smaller pilot facility
- Measurement uncertainties around 1%-- amounting to 80 kg of plutonium per year at a 800 tHM/year facility. Given the inevitable uncertainties in accounting, it is likely that it will ultimately have to rely primarily on other measures to prevent insider theft.
- It is far easier for insiders to steal small amounts of material over time without anyone noticing at bulk processing facilities (e.g. reprocessing, fabrication).
- The increasing shipments among those plutonium separation and recycling facilities would pose more security risks.

The risk of SNF at reprocessing plant

--A reprocessing plant has even greater pool storage capacity than a reactor pool.

--The buildings that house the pools could be even weaker than those pools at reactor sites.

--Most of the sabotage scenarios conceivable for reactor pools could be applied to these pools at reprocessing plants.

--However, for those relative older NSF, would be difficult to ignite automatically in the absence of cooling.

Some ways to cause a significant radioactive release by a successful terrorist attack, e.g.:

--A two- or multiple-stage attack by truck bombs, aircraft impacts or other kinds of on-site explosion could at least breach the zircaloy cladding or even partly melt the fuel cladding.
---Even though this would not ignite a spent fuel fire, a significant fraction of Cs-137 in the rods could be released into the atmosphere.

The risk of SNF at reprocessing plant (cont'd)

Some ways to cause a significant radioactive release by a successful terrorist attack, e.g.:

--Terrorists could pour fuel in the pool and start a fire that would cause ignition of the zircaloy cladding and lead to a greater release of the Cs-137 inventory.

Some Studies indicate that heating at 1,500 °C of high-burnup spent fuel for one hour caused the release of 26% of the Cs inventory.--*NRC, Advisory Committee on Reactor Safeguards, Public meeting, April 9, 1999.*

--Sabotage of HLW tank at reprocessing facilities

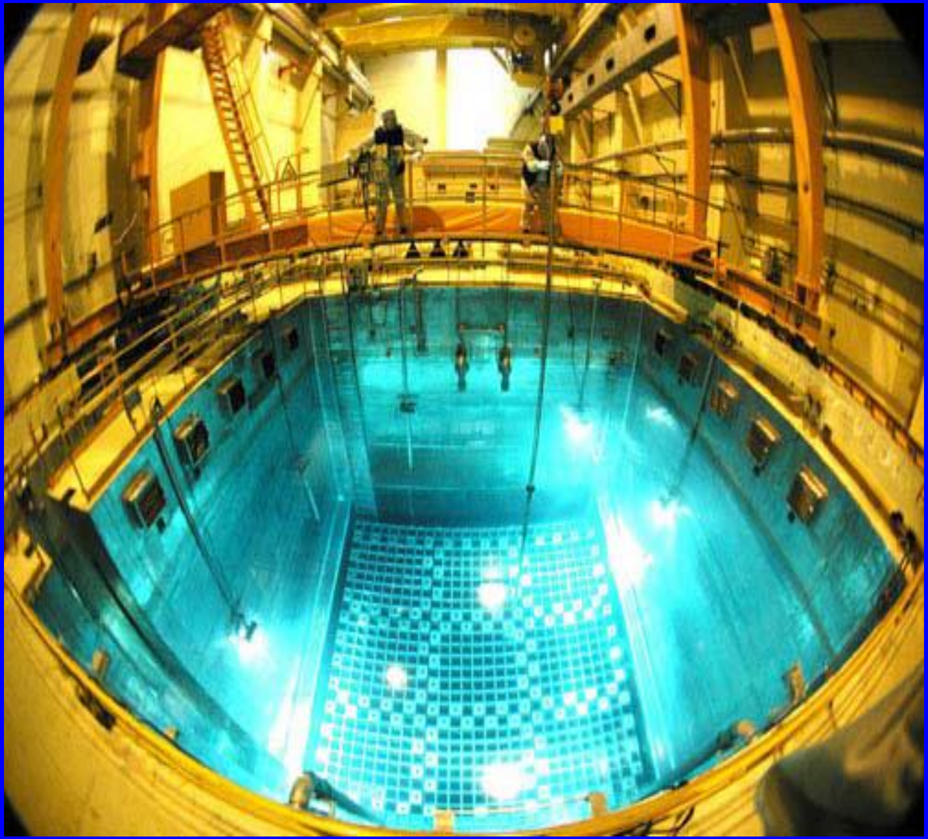
--Release liquid HLW into the sea or other water system

--Nuclear criticality event

--Stolen spent fuel and HLW dispersal by fire lofting

The nuclear safety risks of reprocessing

- **In the past, about 17 accidents at reprocessing plants that led to radiological releases, including fires, explosions, leaks, and criticality accidents.**



More can be read : Gordon R. Thompson, *Radiological Risk at Nuclear Fuel Reprocessing Plants* (Cambridge, Mass.: Institute for Resource and Security Studies, July 2014).

Summaries and suggestions

---The new study shows that China's reprocessing and plutonium recycle is much more costly than LWR once-through cycle.

---Enough U for many decades, even under the most ambitious scenarios. To secure long-term uranium supplies for its fast-growing nuclear power industry, China should continue maintaining its one-third policy: domestic uranium, international market, overseas mining.

---Reprocessing increasing concerns on nuclear proliferation, nuclear security and safety issues .

---Should postpone the large reprocessing plant, and take an interim storage approach, which offers a safe, flexible ,and cost-effective near term approach to spent fuel management.

---The postponing approach will give China a substantial opportunity to carefully develop a long-term policy for the nuclear fuel cycle.