HARVARD Kennedy School
BELFER CENTER
FOR SCIENCE AND INTERNATIONAL AFFAIRS

The Economics of Reprocessing and Recycling vs. Direct Disposal of Spent Nuclear Fuel

Matthew Bunn

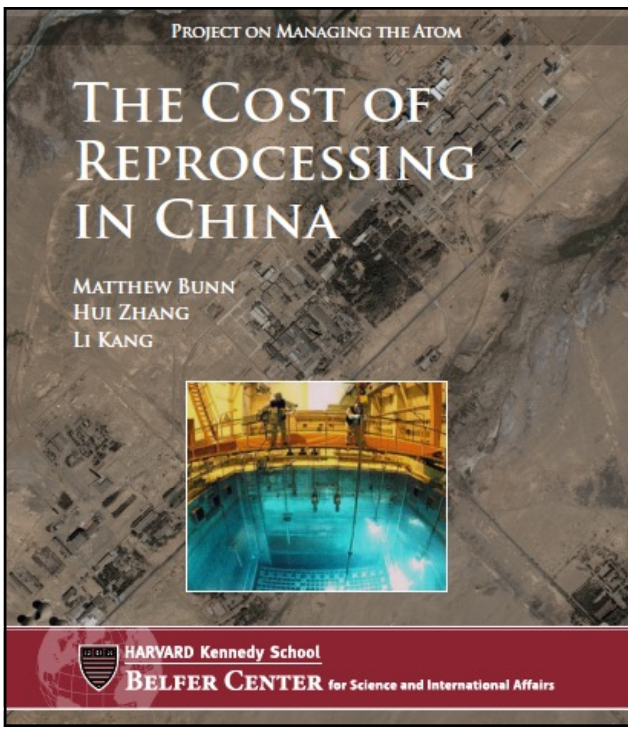
James R. Schlesinger Professor of the Practice of Energy, National Security, and Foreign Policy, Harvard Kennedy School

Briefing to National Academies Committee on Advanced Reactors and Fuel Cycles

7 June 2021

belfercenter.org/managingtheatom

1



- Major 2014 report
  - Bunn, Zhang, and Kang contributors
  - Chinese cost extrapolations from pilot plant
  - Comparisons to international experience
- China could save many billions by storing spent fuel rather than reprocessing it
- https://tinyurl.com/ybtsaqvs

2

THE ECONOMICS OF REPROCESSING
VS. DIRECT DISPOSAL OF SPENT NUCLEAR FUEL

Final Report
8/12/1999-7/30/2003

Matthew Bunn
Steve Fetter
John P. Holdren
Bob van der Zwaan

December 2003
DE-FG26-99FT4028

PROJECT ON MANAGING THE ATOM
BELFER CENTER FOR SCIENCE AND INTERNATIONAL AFFAIRS
JOHN F. KENNEDY SCHOOL OF GOVERNMENT
HARVARD UNIVERSITY
79 JOHN F. KENNEDY STREET
CAMBRIDGE, MASSACHUSETTS 02138

- 2003 report
  - Bunn, Fetter, Holdren, van der Zwaan contributors
  - In-depth examination of demonstrated costs of reprocessing, recycling
  - Reprocessing much more expensive than once-through
- Summarized in 2005 *Nuclear Technology* article
- https://tinyurl.com/y6nmabxk

3

A simplified summary: One kilogram of MOX is > 6x as expensive as one kilogram of LEU

4

1 kilogram LEU

Item	Quantity	Price	Cost
U	11	$100/kgU	$1100
Conv.	11	$12/kg	$130
Enrich.	6.5	$80/SWU	$530
Fab.	1	$400	$400
Total			$2160

1 kilogram MOX

Item	Quantity	Price	Cost
Repro.	6	$2000/kg	$12000
U	<1	$0	$0
Fab.	1	$3000/kg	$3000
Total			$15000

- For equal cost, U would have to get FAR more expensive, or reprocessing would have to get FAR cheaper
- MOX Is more expensive even if the plutonium is “free”

4

Another simplified approach: Reprocessing far more expensive than storage and disposal

5

1 kilogram spent fuel for disposal

Item	Cost
Storage	$200/kgU
Disposal	$400/kgU
Total	$600/kgU

1 kilogram spent fuel for reprocessing

Item	Cost
Reprocessing	$2,000/kgU
HLW Disposal	$200/kgU
Total	$2,200/kgU

- Value of recovered plutonium is negative in current market; value of recovered uranium is modest
- For equal cost, disposal would have to get FAR more expensive, recovered materials would have to get FAR more valuable, or reprocessing would have to get FAR cheaper

5

A fuller view: Reprocessing and recycle greatly increase full fuel cycle costs

6

- Case 1: LEU direct disposal vs. recycling as MOX in LWRs
  - We assume fairly high costs of U and of direct disposal
  - We use low estimate of cost for 800 tHM/yr plant, low MOX cost estimate, exclude higher disposal cost of MOX fuel
  - Result: reprocessing increases fuel-cycle costs by 2/3: $2.46 $/MW-hr to $4.16/MW-hr (smaller impact on total electricity cost)
- Case 2: LEU direct disposal vs. breeders
  - Same favorable assumptions for reprocessing
  - We assume breeders only 20% more expensive to build – modest increases in operations cost as well
  - Result: total electricity cost increases ~20% for electricity from breeders
- In both cases, U would have to rise to ~$450/kgU for reprocessing to be economic

6

Reprocessing: a history of commercial failure

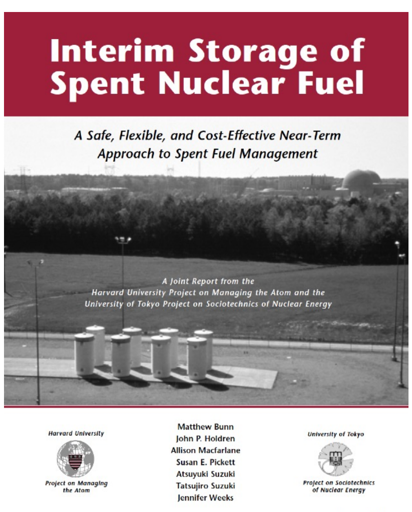
7

- UK:
  - THORP reprocessing plant bankrupted British Nuclear Fuels, Limited – even though it was built with no-interest money from pay-ahead contracts
  - Now closed, owned by Nuclear Decommissioning Authority
- France:
  - Most "successful" program
  - Government study concluded reprocessing added >$10B to the cost of France's nuclear program
  - Operating at ~1/2 capacity, foreign customers not interested
- Japan:
  - Rokkasho plant any billions over budget, decades behind schedule
  - So expensive utilities demanded and got a government bailout – wires charge increasing price for all users of electricity in Japan

7

Dry cask storage provides a cheap, safe, secure alternative that leaves options open

8



- Typically <$200 kg/HM for decades of storage
- Leaves all options open – reprocessing, direct disposal
- Low risks of accident or sabotage
  - Especially if inside building or behind berm
- Widely used in many countries
- Main issue is public acceptance – but many sites have succeeded in siting

8

Reprocessing: financing costs crucially affect per-kilogram costs

9

- Consider: hypothetical 800 tHM/yr reprocessing plant
  - Capital cost: $20B
  - Annual operating cost: $1.5B
  - Decommissioning cost: $0.4B (likely much too low)
  - Operates at 100% capacity for 40-year life (unrealistic)
- If cost of money is 0% per year (unrealistic):
  - $3,200/kgHM
- If cost of money is 3%:
  - $4,000/kgHM
- If cost of money is 6%:
  - $5,400/kgHM

Reprocessing cost in previous calculations was below the low end of these estimates, to be generous to the case for reprocessing

9

Last U.S. effort to produce plutonium fuel was <u>far</u> more expensive than expected

10

- Original idea was that MOX in existing reactors would be a modest-cost approach to plutonium disposition
  - Value of the fuel would pay for part of the cost
  - Net life cycle cost expected to be <$2B
- Decades of delays, billions in cost overruns
- When canceled, net program cost estimate >$40B (no financing cost included), for 34 tons of plutonium
  - $1M/kg Pu!

Source: Areva

10

Items typically left out of many reprocessing cost calculations (incomplete list)

11

- Multiple years to come to full operation (increases IDC)
- Decommissioning costs (proving to be larger than expected)
- Plutonium storage costs, americium separation costs
- Realistic financing rates (different from discount rate for setting aside assured funds for future costs)
- Reprocessing plants typically operate well below capacity
  - Lack of demand and technical problems
- Reprocessing plants generate large volumes of low-level and intermediate-level waste
  - Decommissioning waste volumes may be large, usually ignored
  - Intermediate-level includes TRU-contaminated, requires deep geologic disposal

11

"Advanced" processes do not seem likely to solve the key problems

12

- DOE multi-lab "Advanced Nuclear Fuel Cycle Cost Basis" study:
  - Cost of pyroprocessing of fast reactor fuel integrated with fabrication of fuel from the products $3,000-$9,000/kgHM
  - Vendor projections of low costs for future processing do not match past experience, independent estimates
  - Additional complex separations need for transmutation add complexity, likely add to cost
- National Nuclear Security Administration study of proliferation risks:
  - All spent fuel processing approaches examined have "only minor differences" in proliferation and security risks from PUREX's separation of pure plutonium
  - On a scale from A-Z, with Z standard PUREX, best of these processes rated a W

12

So far, fast neutron reactors have had higher capital costs than LWRs

13

- Decades-long history of high cost, low capacity-factor for prototype fast neutron reactors
  - >$100B invested in R&D globally – no commercially viable reactor has resulted so far
- Russian Minister of Atomic Energy Rumiantsev (2003):
  - "Life has proved that a VVER-1000 reactor [a modern Russian LWR] is one and a half times cheaper than a BN [fast neutron] reactor…[LWRs] are cheaper, safer, and economically more viable."
- Vendors argue new designs will be cheaper than LWRs – but long history, for many designs, of real costs being far higher than initial vendor estimates

13

There's plenty of uranium

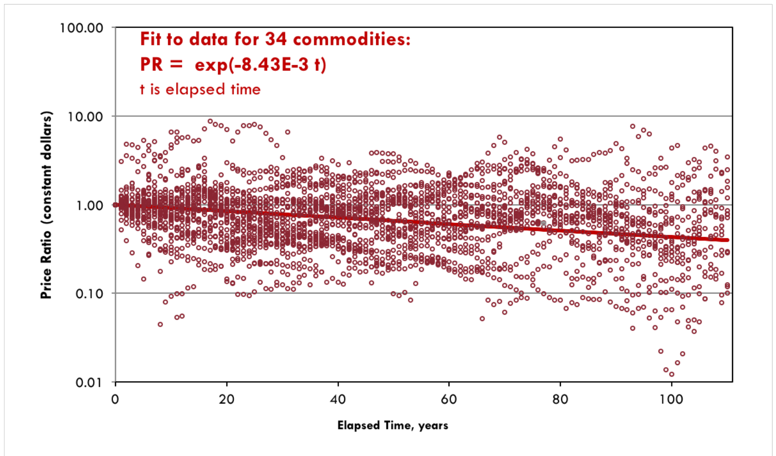
14

- Uranium is abundant
  - Current use ~ 60,000 tU/yr
  - IAEA estimates 15.8 M tU available (known+speculative)
  - U being found faster than it's being used
  - 2010 MIT analysis suggests enough U to fuel 10x current nuclear fleet for *1,000 years* before price increases enough to make reprocessing economic
  - U from seawater *might* turn out to be competitive with reprocessing and fast reactors (substantial R&D progress in recent years)
  - U resources not likely to be an important constraint on nuclear growth this century

14

Real-world prices of mined resources

15



Source: Eric Schneider

15

Waste management benefits are limited

16

- Volume reduction:
  - Physical volume not a major driver repository cost or risk
  - Large volumes of low-level and intermediate-level wastes (including decommissioning wastes) also have to be considered
- Long-term heat reduction:
  - Significantly less long-term heat from HLW than spent fuel
  - Significantly MORE long-term heat from LWR MOX
- Environmental risk:
  - Actinides not chemically mobile in most geologic environments – other isotopes tend to dominate long-term risk
  - Separating and transmuting long-lived isotopes involves additional complexities, costs
- Public acceptance: Finland, Sweden among 1st to succeed

16

Proliferation risks are substantial

17

- Any state with a reprocessing plant is a political decision away from producing nuclear bomb material
  - Even systems that do not "separate pure plutonium" provide trained personnel, facilities, expertise that could substantially reduce time, cost, uncertainty in moving to a weapons program
  - Safeguards on reprocessing plants are challenging and costly
  - Even reprocessing in nuclear-weapon states may make it more difficult to convince other states they do not need to do the same
- Long-term "plutonium mines" appear to be a modest part of the overall proliferation problem
  - Safeguards likely to be maintained as long as nuclear energy is in use anywhere
  - Should not make significant near-term problems bigger to make potential very long-term problems modestly smaller

17

Safety and security risks are significant

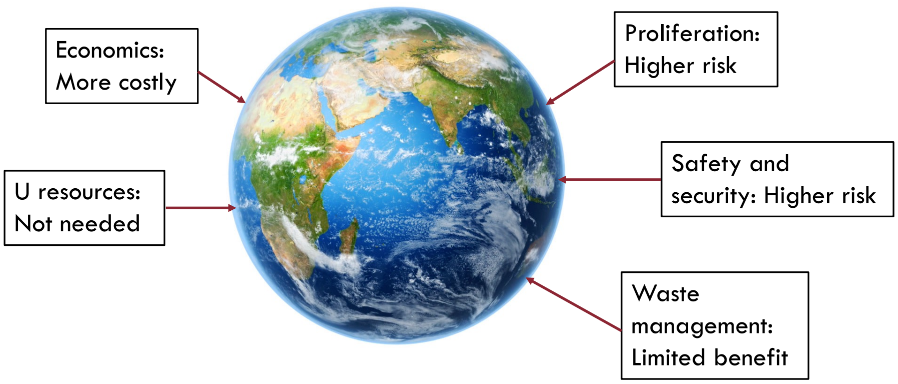
18

- Fuel cycles involving bulk processing of weapons-usable nuclear material create additional risks of nuclear theft
  - ~ 20 cases of seizure of stolen plutonium or HEU in unclassified literature – almost all in bulk forms
  - Multiple government studies have concluded it is plausible terrorists could make a crude nuclear bomb if they had the material
- Processing intensely radioactive spent fuel at high temperatures with volatile chemicals inevitably creates additional pathways for accident or sabotage
  - Long record of fires, leaks at reprocessing plants – including largest pre-Chernobyl accidental release
  - Tanks of liquid HLW – if not solidified immediately – pose particular safety and security challenges, as do enormous spent fuel storage pools

18

A global view

19



- Future of nuclear energy is best served by making it as cheap, safe, secure, proliferation-resistant, simple as possible
  - Reprocessing with known technologies points in the wrong direction on every count

19

For further reading…

20

- *Plutonium Separation in Nuclear Power Programs: Status, Problems, and Prospects of Civilian Reprocessing Around the World* (Princeton, N.J.: International Panel on Fissile Materials, 2015), http://fissilematerials.org/library/rr14.pdf
- Cochran, Feiveson, Patterson, Pshakin, Ramana, Schneider, Suzuki, and von Hippel, *Fast Breeder Reactor Programs: History and Status* (Princeton, N.J.: International Panel on Fissile Materials, 2010), http://fissilematerials.org/library/rr08.pdf
- Kuperman, ed., *Plutonium for Energy? Explaining the Global Decline of MOX* (Austin, TX: Univ. of Texas at Austin, 2018), http://sites.utexas.edu/prp-mox-2018/downloads/
- Bunn, "Assessing the Benefits, Costs, and Risks of Near-Term Reprocessing and Alternatives," testimony, 2006, https://tinyurl.com/y6pbmyz9

20

Backup slides if needed…

21

21

China's pilot reprocessing experience

22

- Construction started 1998
  - Years of delays
  - Large cost over-runs
  - "Completed" in 2005 – but 1st operation 2010
- Design capacity: 50 tHM/yr
- Cost: 3.2B RMB, or $910M (2014 prices, PPP conversion)
- Operated briefly in Dec. 2010
  - Separated 25.4 kg of Pu (counting Pu in solutions separated in later years)
  - Many problems encountered – including substantial MUF
  - Has not operated since (may restart this year)

Source: Gu, "Post-Fukushima Development of Nuclear Energy and Fuel Cycle in China"

22

China's fast reactor experience

23

- CEFR construction started 2000
  - Years of delays
  - Large cost over-runs
  - Completed in 2010
- Design capacity: 25 MWe
- Operations:
  - 1st criticality 7/2010
  - 26 hours in 2011
  - Zero 2012, 2013
  - 72 hours Dec. 2014
  - Intermittently since then (for R&D)

Source: http://news.xinhuanet.com/english2010/china/2011-07/21/c_131000739.htm

23

Chinese capital cost estimates, extrapolated from the pilot plant

24

- 200 tHM/yr reprocessing plant:
  - 4x scale-up from design capacity of pilot plant
  - Rule of thumb for engineering cost extrapolation is that the ratio of costs is equal to the ratio of capacities raised to an exponential scaling factor:

  $C/C_0=(M/M_0)^{\gamma}$
  - For 4x scale-up Chinese experts assume $\gamma=0.9$
  - Hence cost goes from \$910M for pilot plant to \$3.2B
- 800 tHM/yr reprocessing plant:
  - Chinese experts assume $\gamma=0.85$ 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 Chinese experts expect real costs could be higher

24

International experience of reprocessing cost: THORP

25

- Thermal Oxide Reprocessing Plant (THORP), U.K.
  - Built 1985-1994 – financed with pay-ahead contracts
  - Capital cost: £3.07B (1991 BNFL estimate), $7.1B 2014$
  - Operating cost: BNFL early estimate $546M (2014$)
  - Billions in refurbishment, repairs
  - Rapidly escalating estimates of Sellafield decommissioning costs
  - Never performed to expectations; shut-down for years after 2005 leak of plutonium-laden acid into basement holding cell
  - Unable to get additional contracts (dry cask storage cheaper)
  - Planned to shut down once existing contracts completed
  - BNFL bankrupt, facility owned by National Decommissioning Authority

25

International experience of reprocessing cost: UP2-800 and UP3

26

- UP2 and UP3, France
  - Built 1981-1994 – financed with pay-ahead contracts
  - Main remaining contracts EdF, unable to get major new foreign contracts (dry cask storage cheaper)
  - Capital cost: 2010 estimate, €19.5B (>$24B 2014$) for both, roughly $12B for each; 2000 estimate 37B FF ($8 B 2014$) for UP2-800 – difference driven by differing inflation rates, currency conversion rates
  - Operating cost: 2000 estimate, >$500M/yr at full capacity
  - Estimates of decommissioning costs of nuclear plants in France escalating

26

International experience of reprocessing cost: Rokkasho Reprocessing Plant

27

- Rokkasho Reprocessing Plant (RRP), Japan
  - Built 1993-2006 – not yet operational
  - Latest projection: operations in 2018
  - Years of delays, many billions in cost overruns
  - Capital cost: JNFL 2007 estimate ¥2.193T ($20.3B 2014$)
  - No data on additional costs since 2007
  - Operating cost: JAEC 2011 estimate, ~¥160B/yr ($1.5B 2014$) – includes refurbishment costs, some additional costs
  - Decommissioning cost: JAEC 2011 estimate, ¥1.54T (>$15B 2014$)
- French €20B offer suggests they believe costs in China would be more comparable to Rokkasho than to THORP and UP2-800/UP3

27

Comparing reprocessing to dry cask storage: high and low estimates

28

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 if low estimate proved correct, and 800 tHM/yr plant operated at full capacity throughout 40-year life, China would save over $20B by simply storing the same fuel in dry casks for that period
  - >$9B 40-year savings for low estimate of 200 tHM/yr plant

28

The importance of financing in estimating per-kilogram cost

29

- For a facility that costs billions to build, the "cost of money" – interest on a loan or returns on investment – makes a huge difference in total cost
- Even money provided to the builder "free" from the Chinese government is not "free" for Chinese society
  - Could have been spent on other investments with substantial "social rate of return" (compare to average in Chinese economy)
  - Even China's government has to pay borrowing costs
- Report considers 3 cases:
  - 0%/yr real cost of money (company perspective if government pays)
  - 3% real cost of money (combination of investment and low-cost loans)
  - 6% real cost of money (comparable to return on other nuclear investments – or to combination of investments and loans, including taxes and insurance)

29

Per-kilogram reprocessing costs: high and low estimates: 200 tHM/yr plant

30

Plant	Capital Cost	IDC	Decom.	Capital+ IDC+ Decom.	FCR	Capital Charge/ kg	Operating (annual)	Operating (per kg)	Total cost/ kg
200 tHM/yr Low 0%	$3.2B	0	.04	$3.3B	0.025	$520	$190 M	$1,200	$1,700
200 tHM/yr Low 3%	$3.2B	0.19	.04	$4.0B	0.043	$1,070	$190 M	$1,200	$2,300
200 tHM/yr Low 6%	$3.2B	0.42	.04	$4.7B	0.066	$1,950	$190 M	$1,200	$3,100
200 tHM/yr High 0%	$5.7B	0	.04	$5.9B	0.025	$930	$340 M	$2,140	$3,100
200 tHM/yr High 3%	$5.7B	0.19	.04	$7.0B	0.043	$1,906	$340 M	$2,140	$4,000
200 tHM/yr High 6%	$5.7B	0.42	.04	$8.4B	0.066	$3,469	$340 M	$2,140	$5,600

- By comparison, cost of 40-year storage plus direct disposal in range of $900/kgHM (with generous disposal costs) – disposal of HLW will add to reprocessing cost

30

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

31

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

31

Are these the right plants to support China's nuclear plans?

32

- 200 tHM/yr and 800 tHM/yr plants designed to separate plutonium from LWR fuel
  - Likely would need different plants (or major modifications) to reprocess breeder fuel
  - Would need different fabrication plants to make breeder fuel
  - Could easily start breeders with HEU (as with CEFR) or with plutonium from large excess stocks in other countries
  - Even with reprocessing, 800 tHM/yr plant only needed if China builds much larger fleet of breeder reactors than 2 now proposed
- Proposed plants based on decades-old technology
  - Would do little for China's technological leadership to build plant based on old PUREX technology
  - China could invest in R&D facility to explore new technologies that might address some of the problems of past reprocessing technologies – would do more for China's technological leadership

32

Opportunity costs of large reprocessing and fast-reactor investments

33

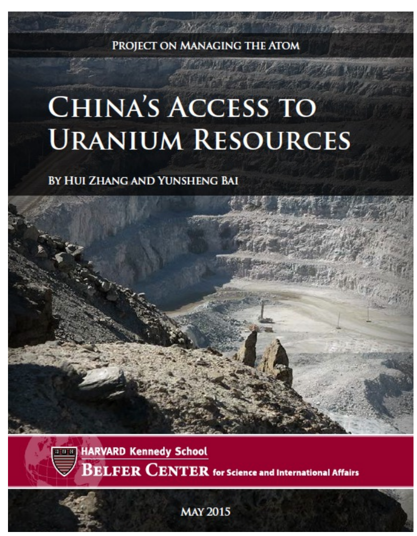
- China could spend the money providing more clean energy for China's grid
  - 40-year excess costs of reprocessing (beyond costs of dry cask storage) would be enough to build ~ 10 GWe of additional nuclear plants (even assuming low cost estimate and zero financing cost)
- Non-economic costs are substantial
  - Reprocessing facilities pose complex challenges for operators, regulators
  - Large number of experts, regulatory effort would have to be devoted to reprocessing and recycling rather than to improving safety, security, and efficiency of China's nuclear reactors

33

China has plenty of uranium

34

- China is continuing to discover U resources, and to purchase U mines abroad
- Global resources are increasing, not decreasing, as U discoveries outpace use
  - Global price trend for mined resources in 20th century was *down,* as improving technology outpaced using up of lowest-cost resources
- China can access enough U to fuel large-scale growth for many decades to come



34

Postponing reprocessing would better serve China's interests

35

- China has the luxury of time
  - Enough U to fuel even aggressive nuclear growth
  - Dry cask storage provides safe, secure, low-cost approach, leaves all options open for the future
  - Postponing allows time for technology to develop, interest on funds to accumulate, security, political, and economic issues to clarify
- Selected recommendations
  - Undertake comprehensive review of options – including all factors
  - Invest in dry cask storage – useful for all fuel cycle options
  - Ensure potential proliferation impact fully considered
  - Design in high levels of safety and security from the outset
  - Avoid accumulating separated plutonium
  - Pursue R&D on fuel cycle technologies

35