Economics of reprocessing

Matthew Bunn
Harvard Kennedy School
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http://www.managingtheatom.org

Reprocessing issues

- The choice of whether to focus on open or closed fuel cycles must be based on a complete life-cycle assessment of several factors:
  - Economics
  - Uranium supply
  - Safety
  - Security (from sabotage)
  - Nonproliferation
  - Waste management
- This presentation focuses on economics – with some remarks on other aspects

Economics summary

- Harvard study: reprocessing and recycle (with quite optimistic assumptions) increases back-end costs ~80%, will not be economic until uranium reaches $360/kgU
  - Full report available at: http://belfercenter.ksg.harvard.edu/publication/2089/
  - MIT Future of Nuclear Energy study: different presentation, very similar results
- NAS panel: additional cost of separations and transmutation for 62,000 tons of spent fuel "is likely to be no less than $50 billion and easily could be over $100 billion."
- AFCI and MIT Future of Nuclear Fuel Cycle studies:
  - MOX fabrication, pyroprocessing, breeder reactors significantly *more* expensive than Harvard or NAS studies assumed, waste management cost reduction from reprocessing *lower*

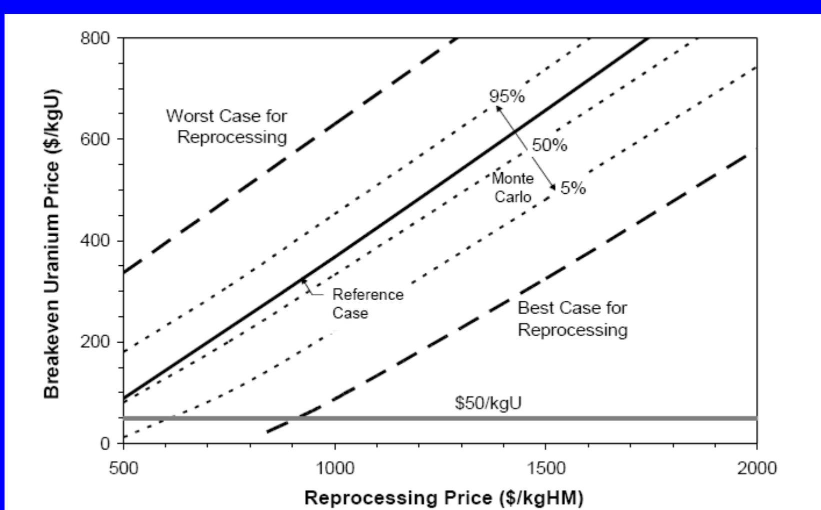
Reprocessing costs – a simplified comparison

- Choice 1: Buy LEU fuel, store, direct disposal
  - 1 kg LEU=7 kg U@$130/kgU+7 kg conv@$10/kgU+6 SWU@$150/SWU+1 kg fabrication@$300/kgHM=$2180/kgHM
  - 40 years storage=$200/kgHM
  - Disposal=$450/kgHM (present cost of future disposal. 1 mill)
  - Total=$2830/kgHM
- Choice 2: Buy MOX from Pu reprocessing, dispose of reprocessing wastes
  - 1kg MOX=Pu from 6 kg reprocessing@$1000/kgHM+1kg MOX fab@$1500/kgHM-$200/kgHM disposal cost advantage -$130/kgU recovered U value=$5520
  - Disposal/Management of spent MOX=$450/kgHM
  - Total=$5970/kgHM
- Choice 2 is twice as expensive (breakeven U price $335/kgU) even with assumptions favoring reprocessing…

Method: calculating breakeven U price

$$\begin{bmatrix}\text{cost of interim storage}\\ +\text{ disposal of spent fuel}\end{bmatrix} = \begin{bmatrix}\text{cost of reprocessing}\\ +\text{ disposal of wastes}\end{bmatrix} + \begin{bmatrix}\text{cost of producing LWR fuel}\\ \text{using recovered Pu, U}\end{bmatrix} - \begin{bmatrix}\text{cost of equivalent}\\ \text{LEU fuel}\end{bmatrix}$$

Breakeven uranium price as a function of reprocessing price



Breakeven values of key parameters

Breakeven prices of selected parameters, assuming U price = $50/kg and central values for other parameters

Parameter	Central Estimate	Breakeven Value	Breakeven / Central
Disposal cost difference	200	630	3.2
Interim spent fuel storage	200	780	3.9
Enrichment ($/SWU)	100	1200	12.0
Reprocessing ($/kgHM)	1000	420	0.42
Uranium ($/kgU)	50	370	7.4

Intentionally conservative

- These estimates of breakeven U price and ΔCOE are low, because of assumptions favorable to reprocessing:
  - Central reprocessing cost estimate far below cost that would pertain in privately financed facilities with costs comparable to those demonstrated at existing plants
  - MOX fuel fabrication estimate well below many recent prices
  - No charge for Pu storage, Am removal, licensing or security for MOX use
  - High cost dry cask storage required for all fuel for direct disposal option – though most new plants designed with lifetime pools
  - HLW disposal cost advantage higher than most current estimates
  - Equal disposal costs for spent MOX and LEU, despite much higher MOX heat

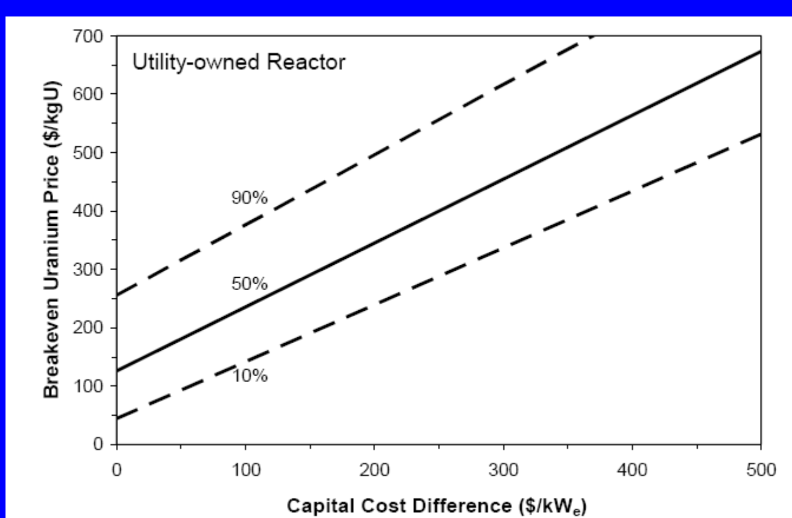
Reprocessing costs: The impact of financing

Assume: Capital, operating costs = reported costs for THORP, (similar to UP3), continuous operation for 30 years at 800 tHM/yr. What is revenue requirement?

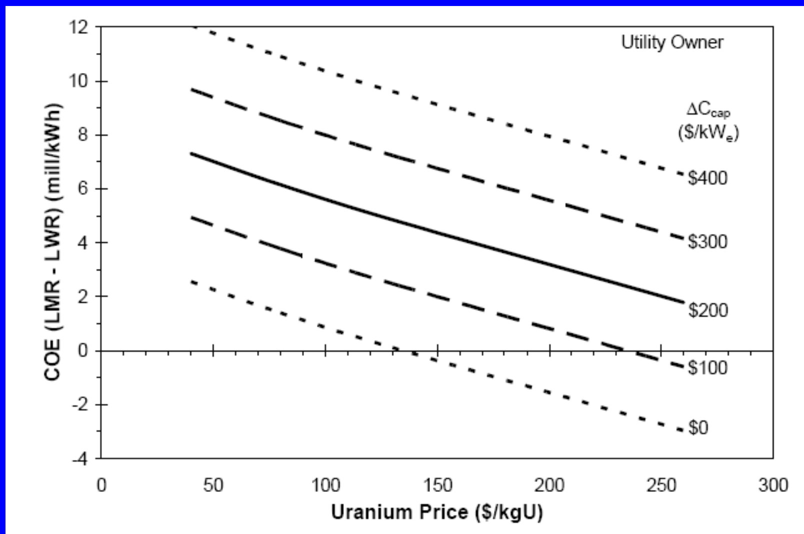
- Government-financed (4% real): $1350/kgHM
- Utility-financed: >$2000/kgHM
- Private venture financed: >$3100/kgHM

- Hence, achieving our $1000/kgHM illustrative figure would already require government financing; fast, low-cost construction; technological improvement; or a combination of all of these…
- Real plants built since then (Rokkasho) have been much more expensive, proposals since then somewhat more expensive

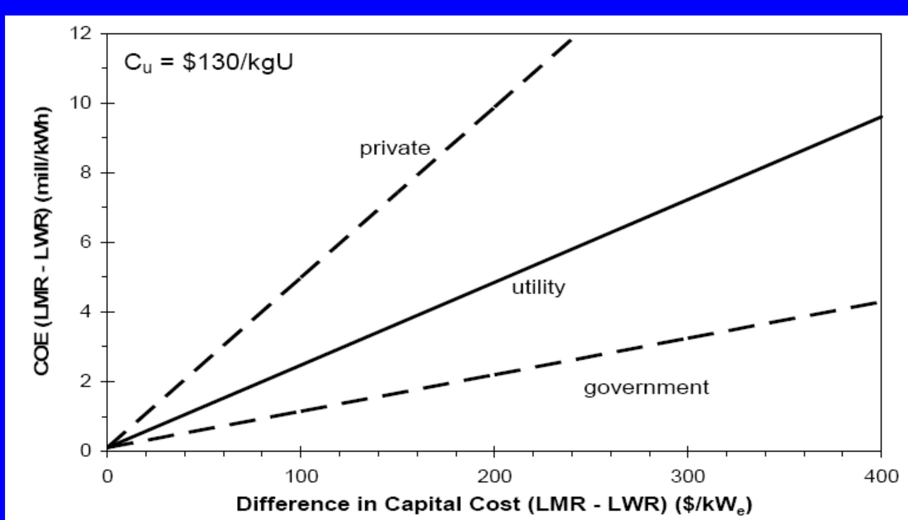
Recycling in fast reactors: Breakeven U price vs. capital cost difference



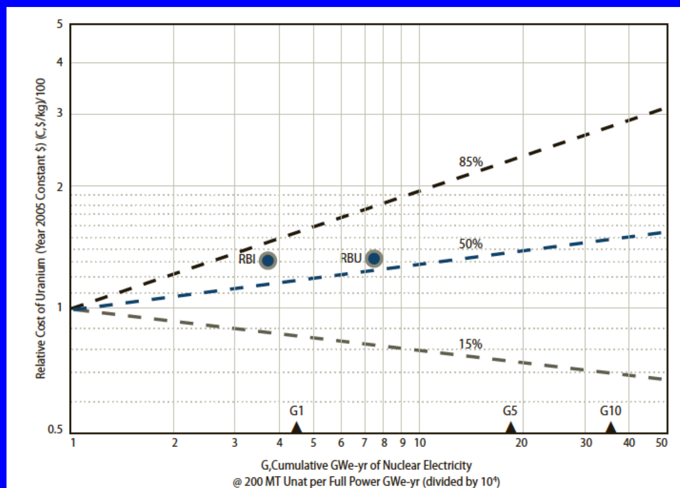
Additional electricity cost for recycling in fast reactors



Impact of ownership/financing on the increased cost of electricity



How much uranium available at costs below those of recycling?



Source: Future of the Nuclear Fuel Cycle, MIT, 2011

What has changed? AFCI and MIT studies project still higher costs

Parameter	Harvard 2003	AFCI 2009	MIT 2010
PUREX reprocessing	$1000/kgHM	$1000/kgHM	$1600/kgHM
Pyroprocessing	$1000/kgHM	$5000/kgHM*	$3200/kgHM
MOX fabrication	$1500/kgHM	$1950/kgHM	$2400/kgHM
Waste disposal advantage	$200/kgHM	$(complex)	$280/kgHM
Extra FR capital costs	$200/kWe	$600/kWe	$800/kWe

* Includes metal fuel fabrication as well

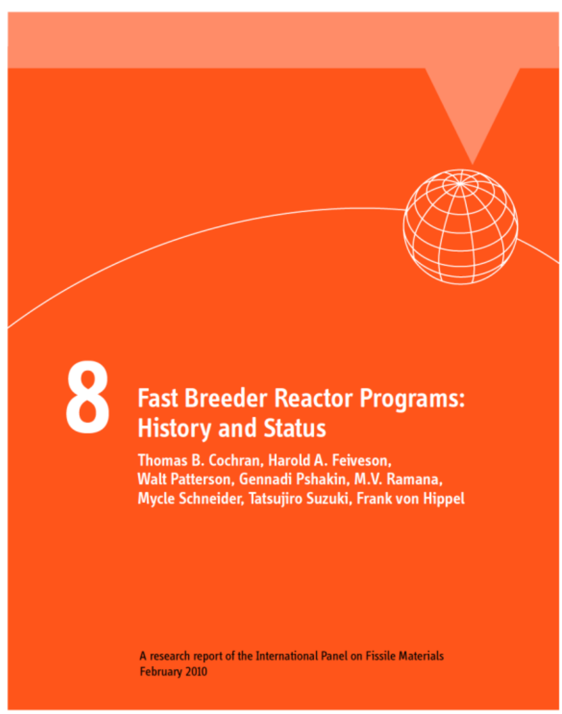
- Nominal or central values in each case
- Harvard assumptions generally more favorable to reprocessing/recycling – still found U would have reach prices not likely to be seen in this century for reprocessing in LWRs or breeders to be economic

Reprocessing economics: other countries' experience

- France: best functioning reprocessing/recycling complex
  - Official estimate: reprocessing all SF will cost >$30B more than not reprocessing any fuel would have cost (Charpin-Dessus-Pellat)
  - Foreign contracts drying up because reprocessing so much more expensive than storage and eventual disposal
- UK: many problems at THORP, SMP failure
  - THORP many years behind schedule, over budget – will close when current contracts worked off
  - BNFL bankrupted, no longer exists
- Japan: Rokkasho still not operating
  - ~$26 billion capital cost of reprocessing plant
  - Costs so high Japanese utilities demanded and got a government bailout – an extra "wires charge" that will make electricity in Japan more expensive for decades to come

- Fast breeders in many countries have a poor operational record
- Higher capital costs than LWRs – main cost of nuclear energy
- Tens of billions spent – still far from market commercialization

http://www.fissilematerials.org/ipfr
/site_down/rr08.pdf



Reprocessing economics: How will China be different?

- Pilot plant: small facilities inevitably more expensive per kilogram processed
- Commercial-scale reprocessing plant:
  - Reported French price (~$15B) significantly *higher* than Harvard study assumed
  - China can build facilities faster, more cheaply than Western countries typically can
  - China can use government funds with low cost of money to reduce the per-kilogram revenue requirement for reprocessing
  - Still, cost of reprocessing unlikely to be below $1000/kgHM in Harvard study – may well be significantly higher

Potential total costs for storage vs. reprocessing and recycling in China

Accumulative costs for three spent fuel management scenarios (2008 US$M).

	With a 0 percent discount rate	**With a 5 percent discount rate**
Scenario 1	319.1	123.9
Scenario 2	13,025.8	4833.3
Scenario 3a (the MOX fuel for LWRs case)[a]	20,264.2	7274.2
Scenario 3b (the plutonium stockpile case)[b]	20,801.8	7646.7

[a] Assuming the uranium price is $100 kgU (2008 US$) at the beginning of the time period for simplicity of calculation.

[b] Not including the construction and operational costs of an interim storage facility for separated plutonium.

Source: Zhou Yun, *Energy Policy, 2011*

Non-economic risks: accidents and sabotage

- Near-term reprocessing is likely to add to risks of accidents or terrorist sabotage:
  - Extensive processing of intensely radioactive spent fuel at high temperatures, with volatile chemicals, compared to:
  - Inert storage in large metal or concrete casks, followed by burial deep underground
- Significant accidents at several major reprocessing facilities:
  - Khyshtym: biggest pre-Chernobyl radiation release
  - Tokai: explosion and fire, small radiation release
  - Tomsk: explosion and fire, small radiation release
  - THORP: major leak into basement, other problems
  - Rokkasho: spent fuel pool leaks, vitrifier problems

Proliferation and theft risks

- Reprocessing would separate plutonium into weapons-usable form, mean processing and transport of tons of plutonium every year
  - Risk of theft, sale to terrorists – requires high levels of security
- If leading nuclear countries such China and the United States reprocess, increases the risk that other countries that might pose a proliferation risk might do likewise
  - Increases risk of proliferation, which both the United States and China oppose
- Risks of 50-50 Pu-U mix from COEX not much less
  - Material could be used directly in a nuclear explosive
  - Any state or group that could make an implosion bomb from Pu metal would have a good chance of separting Pu from U

What are we buying for these costs and risks?

- ***Uranium supply:*** World resources recoverable at costs far below those at which reprocessing would become economic are sufficient to supply an expanding global nuclear enterprise for decades (analysis in recent MIT study)
- ***Repository capacity:*** Recycling in LWRs doesn't help significantly; repository space not likely a problem for China
- ***Repository dose:*** Already small and very long-term; if this is the goal, price is likely billions of dollars/life saved
- ***Repository acceptability:*** Not likely to be a major problem for China – and disposal of HLW likely to be opposed as fiercely as disposal of spent fuel. Finland and Sweden have approved repository sites with full support of local communities – neither reprocesses

Interim storage: they key alternative

- Dry casks can provide cheap, safe, secure storage for decades – leaving all options open
- Dry casks are cheap -- <$200/kgHM
- Allows better decisions when technology has developed; political and economic drivers have evolved; interest on spent fuel management funds has accumulated
- Even emplacement in a geologic repository would leave options open, as repository is expected to remain open, with spent fuel retrievable, for 50-100 years or more
- Hence: no need to rush to decision onlarge-scale reprocessing, can continue R&D to develop better solutions

Backup slides (if needed)

Disposal cost difference – our estimate is favorable to reprocessing

Estimate	(SF-HLW), $/kgHM	HLW/SF
Our report*	200 (100-300)	0.5
1993 OECD-NEA	80	0.57
ANDRA	50	0.62
Gen IV crosscut	100 (50-200)	0.62-0.67

*1 mill=370/kgHM at time of discharge for typical burnup, we assumed $400/kgHM spent fuel, $200/kgHM HLW

Notional cost reduction factor for reprocessing waste in Yucca Mountain

Cost Category	2001 Estimate	Percent of Total	Reduction Factor	Reprocessing Waste Cost
Significantly Driven By Heat				
Repository Construction	$6.1		0.25*1.2	$1.8
Drip Shield	$4.8	19%	0.25*1.2	$1.4
Significantly Driven By Volume, Mass, or Packages				
Repository Operation	$4.9		0.5*1.2	$2.9
Waste Package	$8.5		0.5*1.2	$5.1
Monitoring	$5.9	53%	0.5*1.2	$3.5
Surface Operations	$4.9		0.5*1.2	$2.9
Transportation	$6.0		0.5*1.2	$3.6
Not Affected By Waste Type				
Other Costs	$16.4	28%	0.25*1.2	$4.9
Total	**$57.5**	**100%**	**0.46**	**$26.3**

Breakeven values of other parameters

Breakeven prices of selected parameters, assuming a regulated utility owner, a uranium price of $50/kgU, and central values for other parameters.

Parameter	Central Estimate	Breakeven Value	Breakeven Central
Capital cost difference ($/kWe)	200	–95	
Disposal cost difference ($/kgHM)	200	3400	17
Interim spent fuel storage ($/kgHM)	200	4100	21
Enrichment ($/SWU)	100	570	5.7
Reprocessing ($/kgHM)	1000	< 0	
Uranium ($/kgU)	50	340	6.8

Will increasing repository space price make recycling economic?

- PUREX/MOX Recycle in LWRs: no!
  - buildup of minor actinides when MOX is irradiated means that total decay heat per kWh is similar to once-through
- Separations and transmutation could greatly reduce decay heat, make it possible to put waste from much larger number of kWh in same volume, but…
  - reprocessing, fabrication for S&T likely to be more expensive
    - Gen-IV: $2000/kgHM reprocessing, $2600/kgHM core fab
    - NEA S&T study similar estimates
    - Even if U price = $130/kg, ΔCOE = 6 mill/kWh + 10 mill/kWh for capital cost difference = $200/ kW_e
    - Disposal price would have to increase to >$3,000/kgHM, many times current estimates, for S&T to be economically attractive

Will increasing repository space price make recycling economic? (cont.)

- Political barriers to repository expansion are unlikely to make this surcharge attractive
  - Fixed limit on repository space applies only to United States: other countries can greatly expand repositories without new site
  - Assumes political barriers to recycle lower than those to an additional repository, despite lower risks to current population of repository
  - Assumes will not be possible, even decades in the future, to ship spent fuel from one country to another for disposal – even if repository space has become so scarce that utilities are willing to pay huge prices for it and enormous profits can be made by accepting spent fuel
- Close examination is likely to reveal ways to substantially expand capacity in Yucca Mountain without processing (e.g., double-decker or triple-decker repository)
- Time to debate: dry cask storage adequate for decades

Repository environmental impact

- If GNEP approach meets goals, could greatly reduce radiotoxicity and lifetime of wastes to be disposed of in geologic repository
- *But*, projected doses to humans and the environment from geologic disposal already very small – reducing them further has small benefit
- If this is the main goal, appears likely that cost would be billions of dollars for each life saved – thousands of years in the future
- Moreover, reduced repository impact comes with likelihood of increased near-term impact from reprocessing, fuel fabrication, and transportation of highly radioactive transmutation fuels (balanced in part by reduced U mining)

Sustainability: uranium resources

- U resources recoverable at prices below those at which recycling would be justified are likely to be sufficient to fuel an expanding nuclear energy enterprise for many decades
- "Red Book" estimates of U resources rose significantly in last decade, even with little uranium exploration – more will be found now that high prices are motivating exploration
- Current price run-up has nothing to do with lack of U in the ground, everything to do with constraints on rapidly bringing additional production on-line; but over time, profits to be made will motivate additional production
- Reliance on recycling is *not* a path to energy security – as unforeseen events across the globe (or at home) can play havoc with a country's plutonium programs

Sustainability: repository space

- GNEP advocates argue that it will be impossible to license a 2nd repository, hence fuel cycle must be designed to put all future wastes from growing nuclear enterprise in Yucca Mountain
- Latest estimates suggest Yucca Mountain can hold far more spent fuel than some claim – 260,000-570,000 tons
- Argument only holds for United States – other countries siting repositories in wide areas of rock where tunnels can simply be extended
- Reprocessing and transmutation facilities – including scores of fast-neutron reactors – likely to be at least as difficult to gain approval for as the next ridge over at Yucca Mountain
- Once space becomes scarce and price utilities willing to pay goes up, countries may be willing to take others' spent fuel

Proliferation risks (II)

- Near-term U.S. reprocessing likely to make President Bush's goal of stemming the spread of reprocessing capability more difficult to achieve
  - New U.S. message is "reprocessing is essential to the future of nuclear energy, but you're not allowed to have it"
  - Likely to make it more difficult to convince states such as S. Korea and Taiwan not to pursue reprocessing
  - U.S. *should* work with other states to offer cradle-to-grave "fuel leasing" – gives states new incentives not to bother with their own enrichment and reprocessing – but U.S. reprocessing not needed for that purpose
- Risk of "plutonium mines"
  - Centuries from now, world will look very different, Pu in spent fuel in deep repositories unlikely to be major proliferation driver
  - Should not increase significant short-term risks to reduce small, highly uncertain long-term risks

Problems with the BCG study

- Estimates unit cost of $620/kgHM for *both* reprocessing and MOX fab – much less than real plants have achieved for either process
- Achieves this by:
  - Using low 3% government rate (OMB insists on 7% for such projects)
  - Assuming large increase in capacity at minor additional cost
  - Assuming never has any contract or technical delays, so dramatic increase in throughput – unrealistic
- Variety of other unrealistic assumptions
- By contrast, real experience of using Areva technology in U.S. (SRS MOX plant) has resulted in costs many times *higher* than in France – unmentioned by BCG

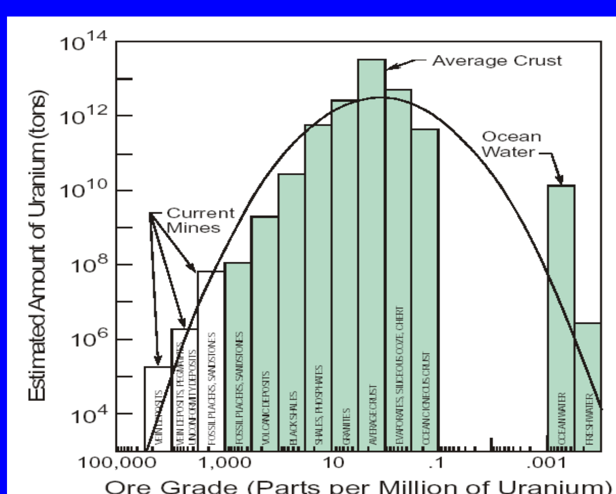
Paper based on 2003 Harvard study – What the study includes

- Does *not* address all elements of the reprocessing vs. direct disposal debate – focuses only on economics
- Asks the questions:
  - Which is more expensive, for a given unit of spent fuel – sending it to direct disposal, or reprocessing it and recycling the plutonium and uranium, and by how much?
  - By how much would the costs of the various parameters have to change to change the answer? In particular, for various possible future reprocessing costs, what price would uranium have to reach for reprocessing to become economic?
- Focuses primarily on PUREX reprocessing and MOX recycle in LWRs, but also considers fast reactors, and briefly discusses separations and transmutation – including issue of repository space

Recoverable U resources – exponential models

Source	ε	MtU recoverable at price less than		
		$40	$80	$130
UIC (doubling price creates ten-fold increase in measured resources)	3.32	2.1	21	105
Deffeyes and MacGregor (ten-fold decrease in concentration = 300-fold increase in resource, p ~ c)	2.48	2.1	12	39
Gen-IV (based on U.S. reserves for various mining methods)	2.35	2.1	11	34
Red Book		2.1	11	16

Deffeyes and MacGregor (1980)



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Early reprocessing: good or bad for the nuclear revival?

- Governments, utilities, and publics will only support the large-scale growth needed for nuclear energy to be a significant part of the answer to climate change if nuclear energy is made:
  - Cheap
  - Safe
  - Proliferation-resistant
  - Terrorism-resistant
- Near-term reprocessing using the technologies known today (or currently under active development) points in the wrong direction on every count – and may do more to undermine than to promote the future of nuclear energy