The Economics of Reprocessing and Recycle v. Direct Disposal

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Direct-disposal v. Reprocessing-Recycle

- Is it better to dispose of spent fuel directly in geologic repositories, or reprocess it to recover and recycle the plutonium and uranium?
- This question is receiving renewed attention, because of concerns about:
  - accumulations of spent fuel and separated plutonium
  - the capacity of geologic repositories
  - the long-term future of nuclear power
  - links between the civilian nuclear fuel cycle and the proliferation of nuclear weapons

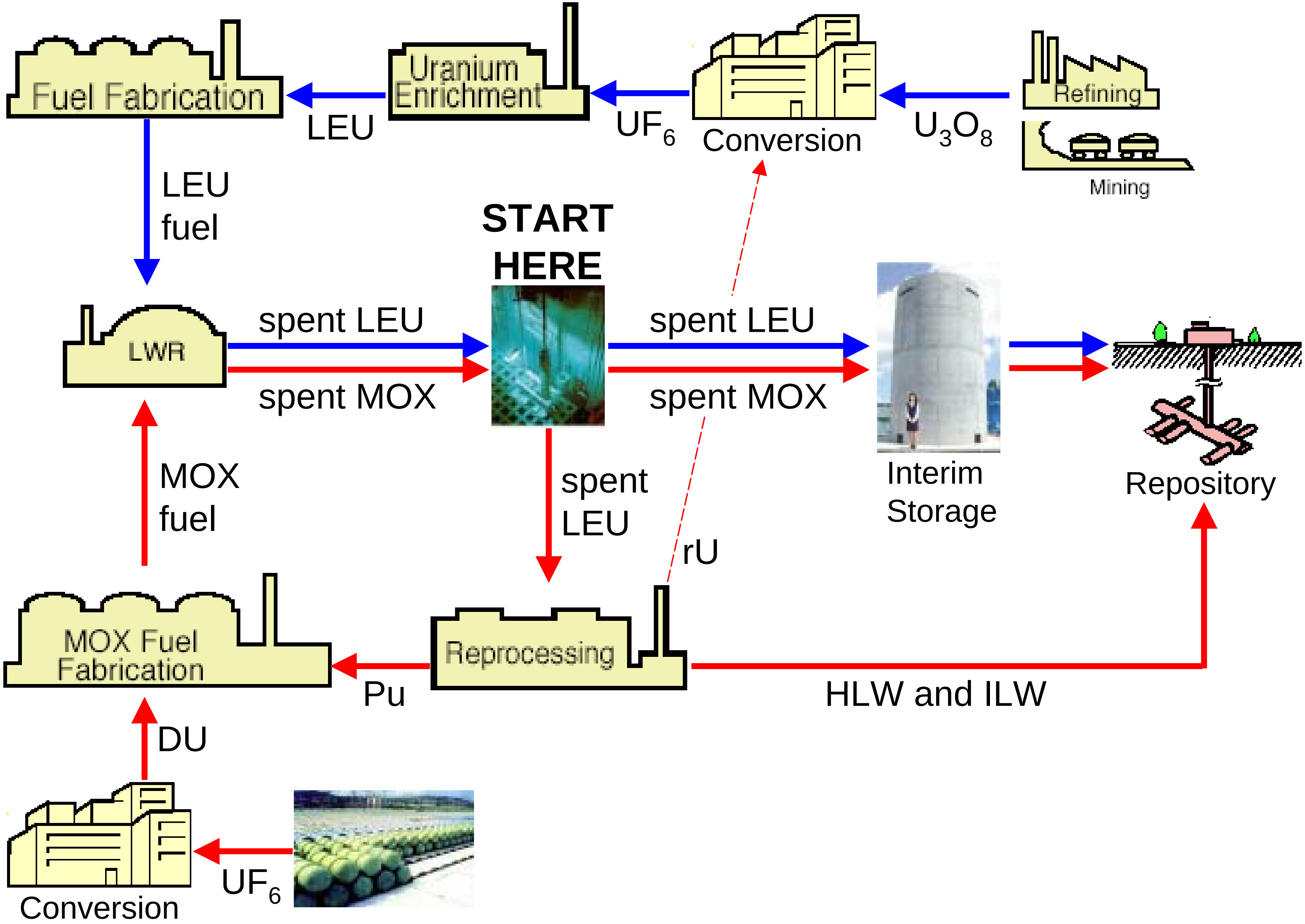
This Study Focuses on Costs

- Cost is an important element in this debate
  - not the only (or most important) factor; environmental, security, and waste-management concerns also important
- General agreement that reprocessing-recycle is more expensive than direct-disposal today
- Advocates argue that difference is small, will disappear soon if nuclear power grows
- We conclude that cost difference is significant and is likely to persist for 50-100 years

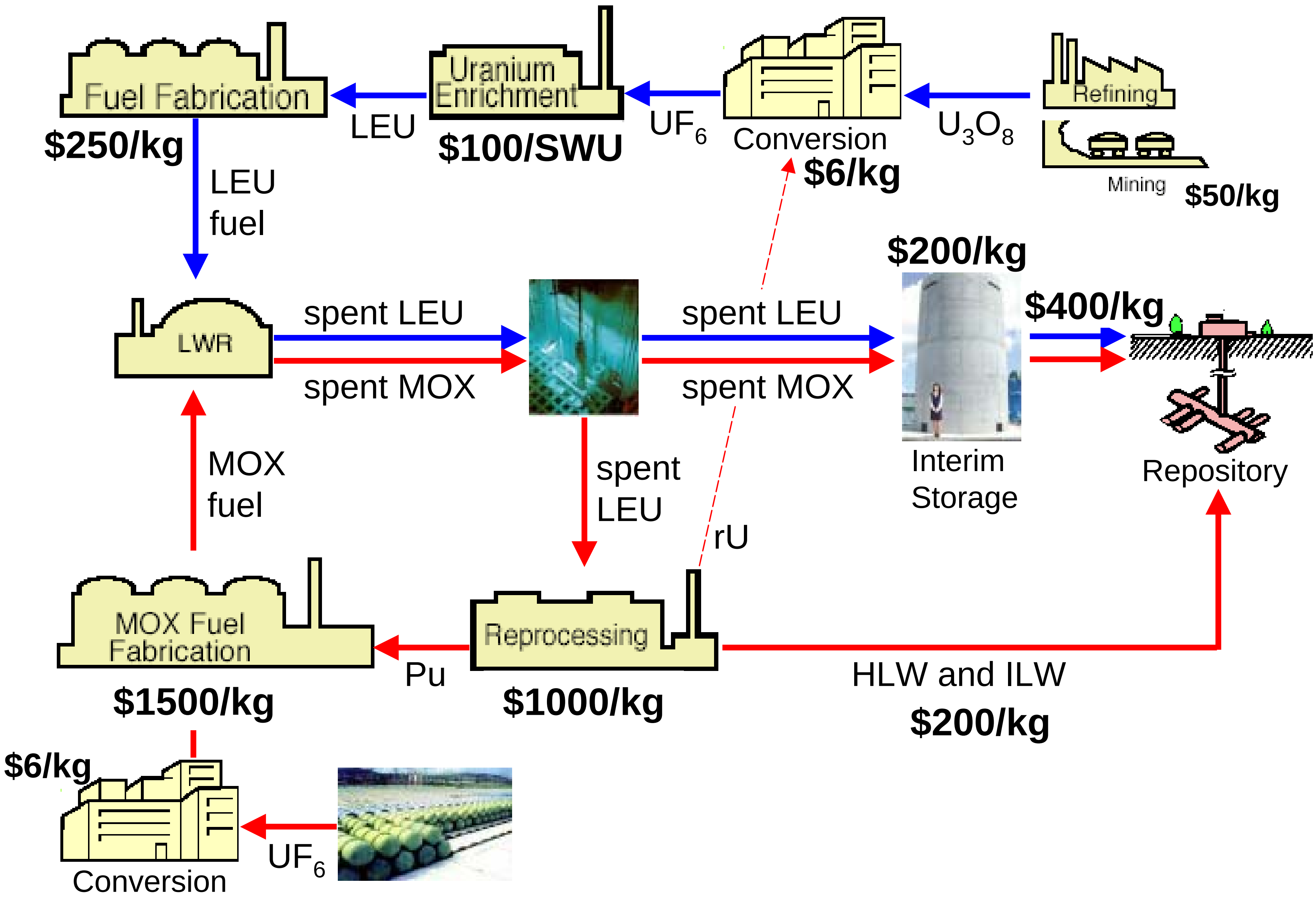
Outline

1. Direct-disposal v. reprocessing-recycle in LWRs
   - breakeven uranium price
   - difference in cost of electricity
   - sensitivity analysis
2. Direct disposal in LWRs v. recycle in FBRs
3. Uranium resources and prices
   - when will uranium price reach the breakeven price for reprocessing-recycle?
4. Impact of reprocessing-recycle on repository requirements

Direct Disposal v. Reprocessing in LWRs



Direct Disposal v. Reprocessing in LWRs



For central values of the price of various fuel-cycle services and other parameters, we calculate

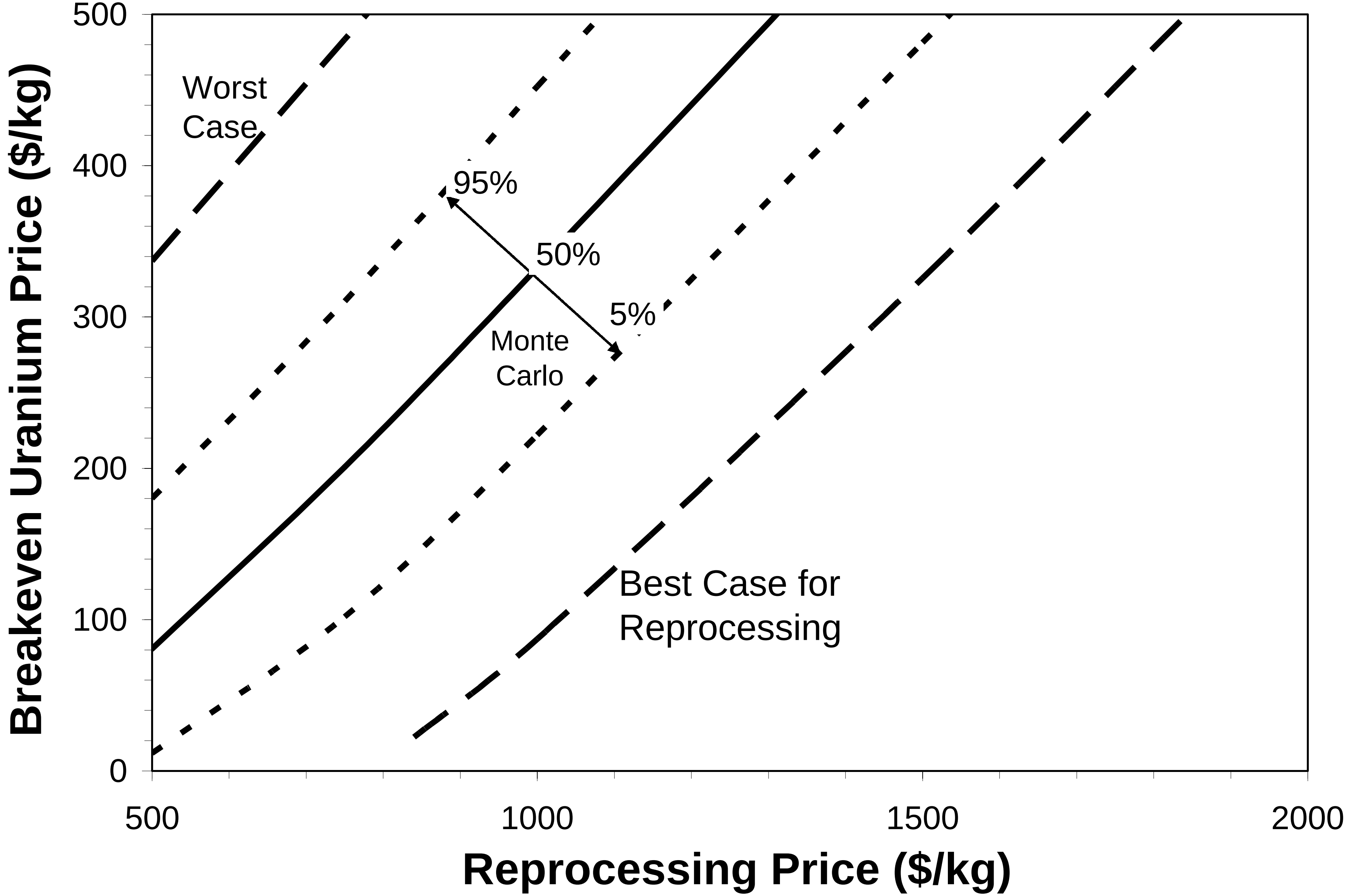
- the uranium price for which the cost of electricity would be the same for both options (the “breakeven price”)
- breakeven prices for other fuel-cycle services (e.g., reprocessing)
- the difference in the cost of electricity (COE), for a given uranium price

Breakeven Prices

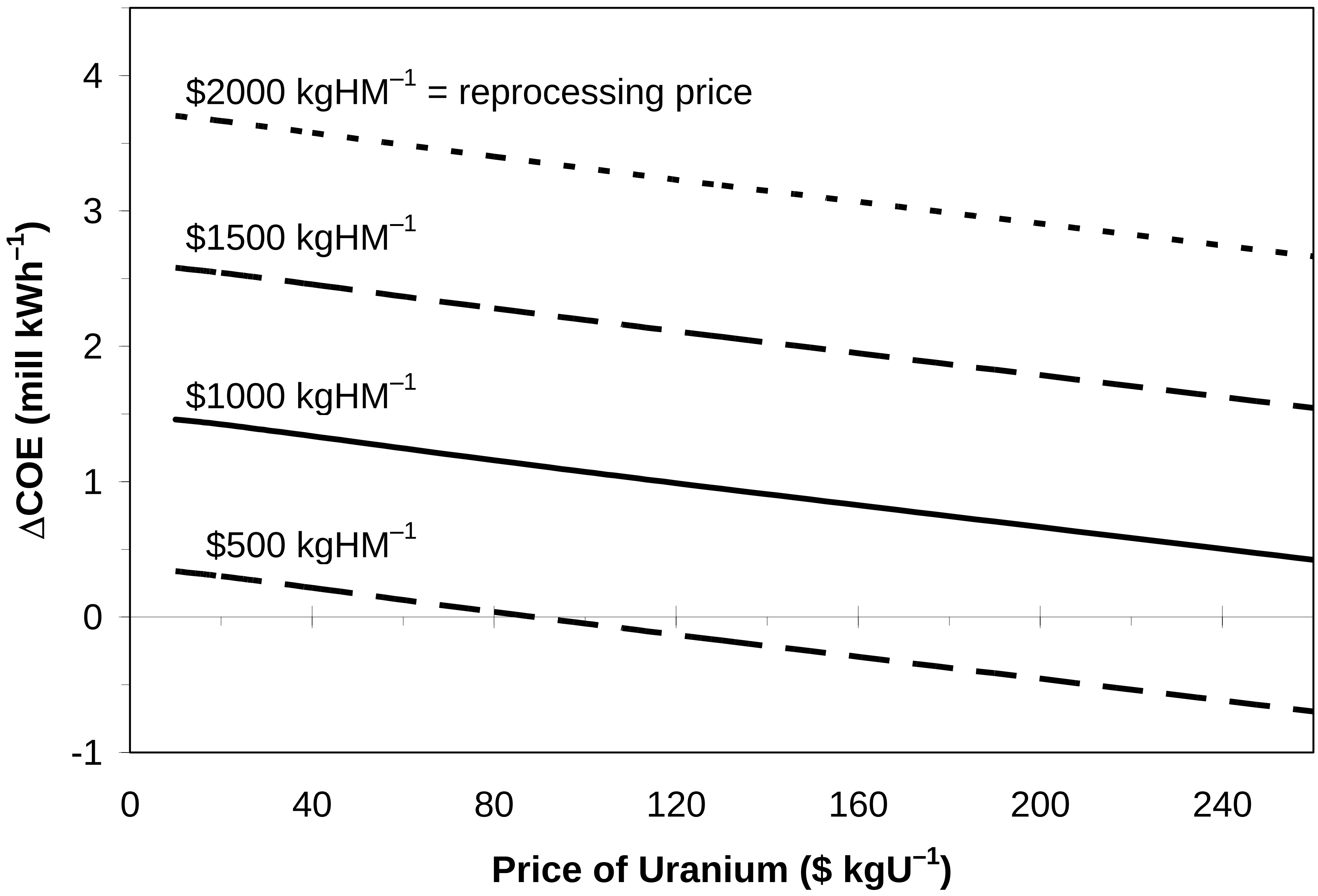
assuming central values of other parameters

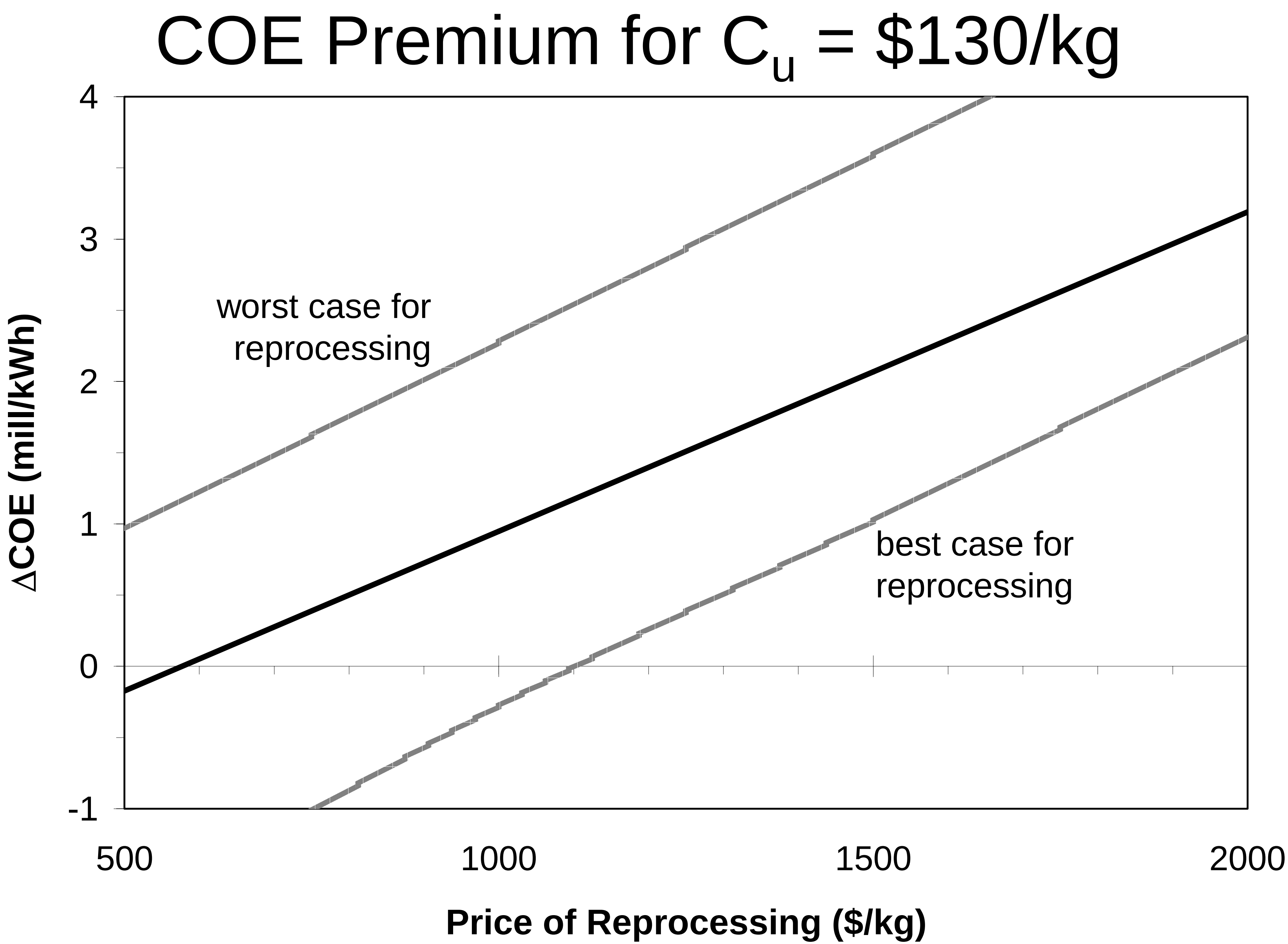
Parameter	**Break-even**	**best**	**central**	**worst**
Uranium ($/kg)	**370**		50	
Reprocessing ($/kg)	**420**	500	1000	2000
MOX fabrication ($/kg)	**<0**	700	1500	2300
Interim fuel storage	**780**	300	200	100
Disposal cost difference	**630**	300	200	100
Enrichment ($/SWU)	**1200**	150	100	50

Breakeven U Price v. Reprocessing Price



COE Premium for Reprocessing-Recycle

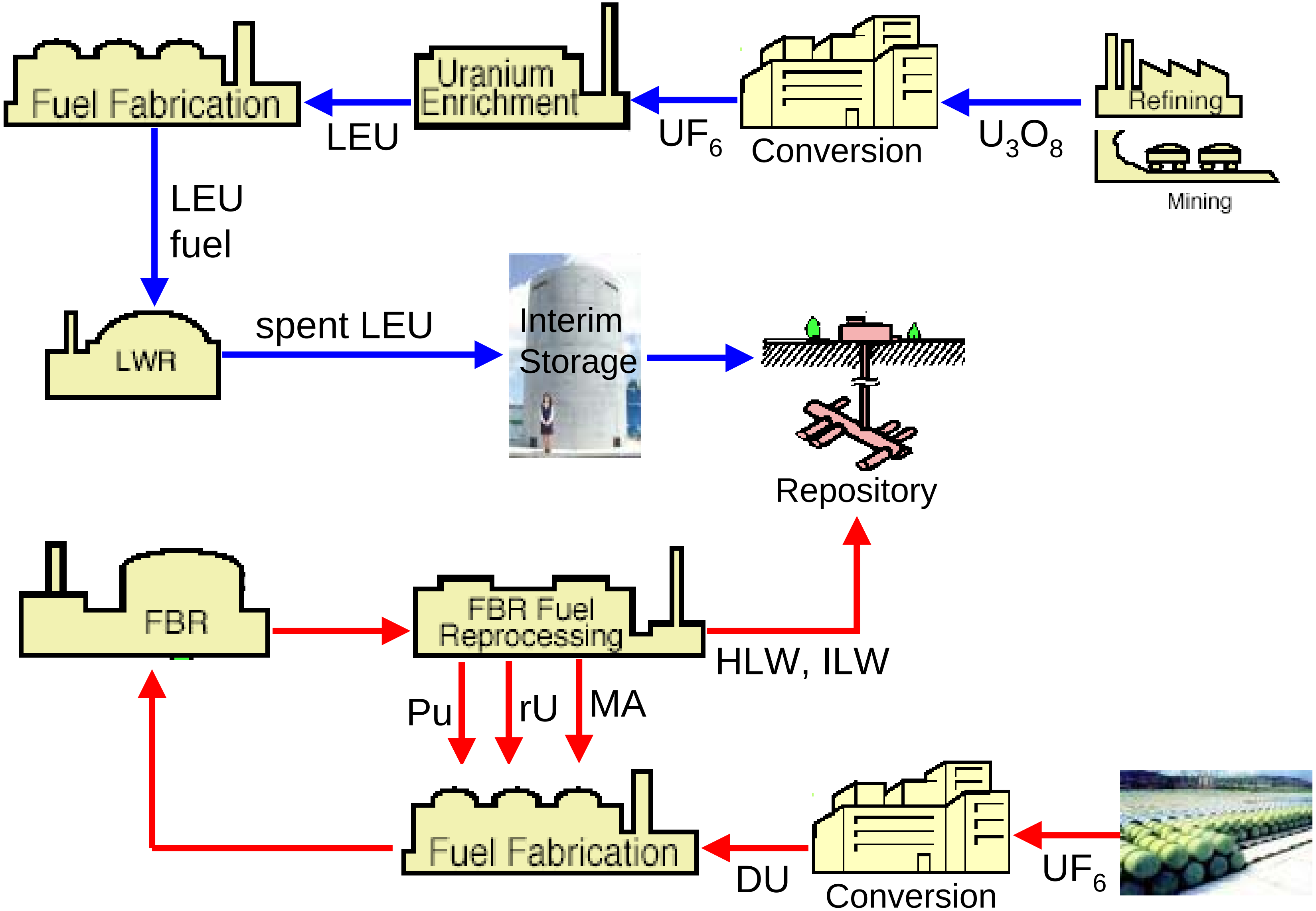



COE Premium for C_u = $130/kg
4
3
2
1
0
-1
ΔCOE (mill/kWh)
worst case for reprocessing
best case for reprocessing
500
1000
1500
2000
Price of Reprocessing ($/kg)

These estimates are <u>favorable</u> to reprocessing

- Central values of reprocessing and MOX fuel fabrication are well below recent prices
- No charge included for Pu storage, Am removal, licensing or security for MOX use
- Expensive interim storage included for direct-disposal
- Disposal cost savings for HLW higher than other estimates
- Equal disposal costs for spent MOX and LEU

LWR (direct disposal) v. FBR

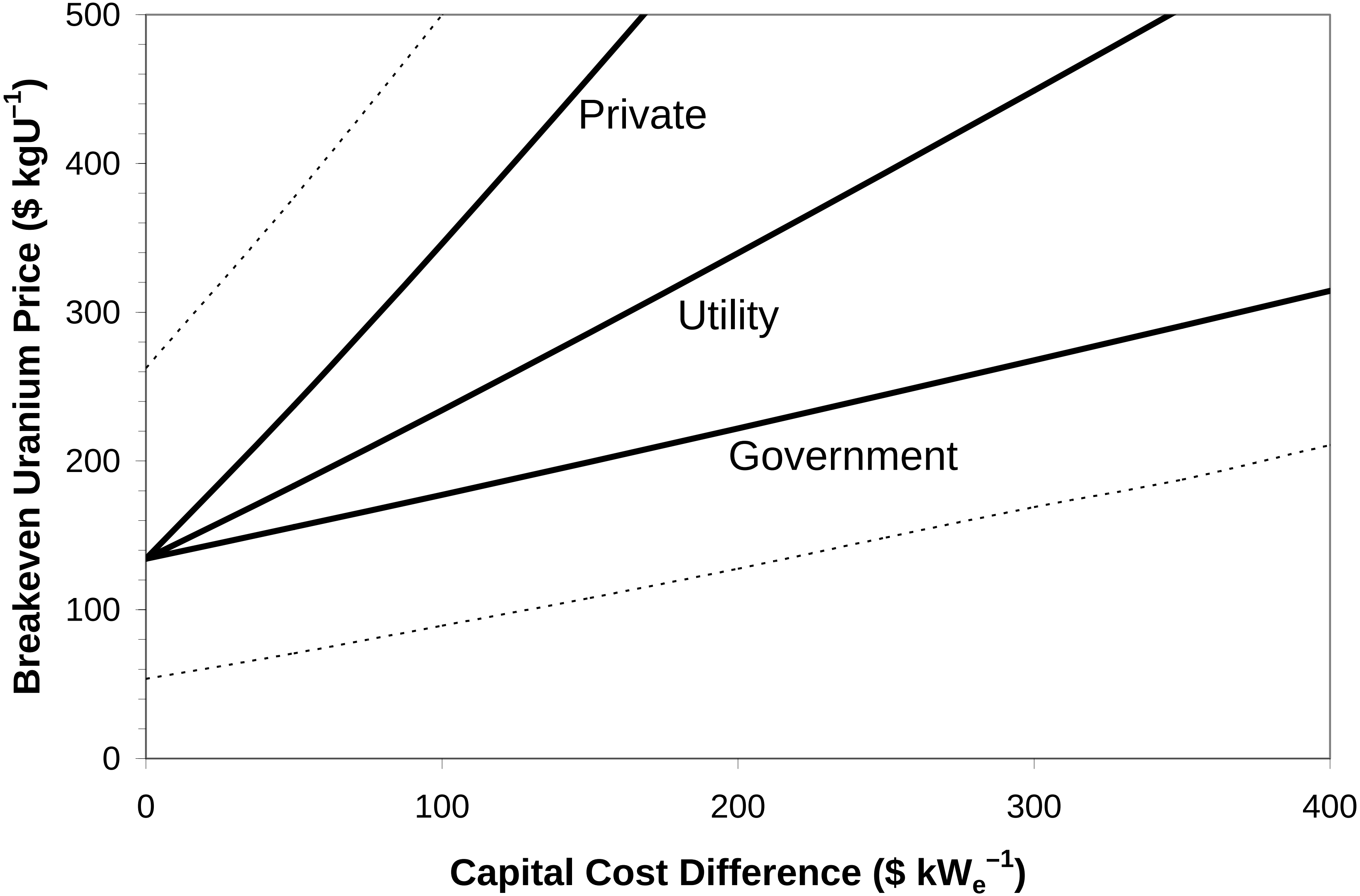


Breakeven Prices

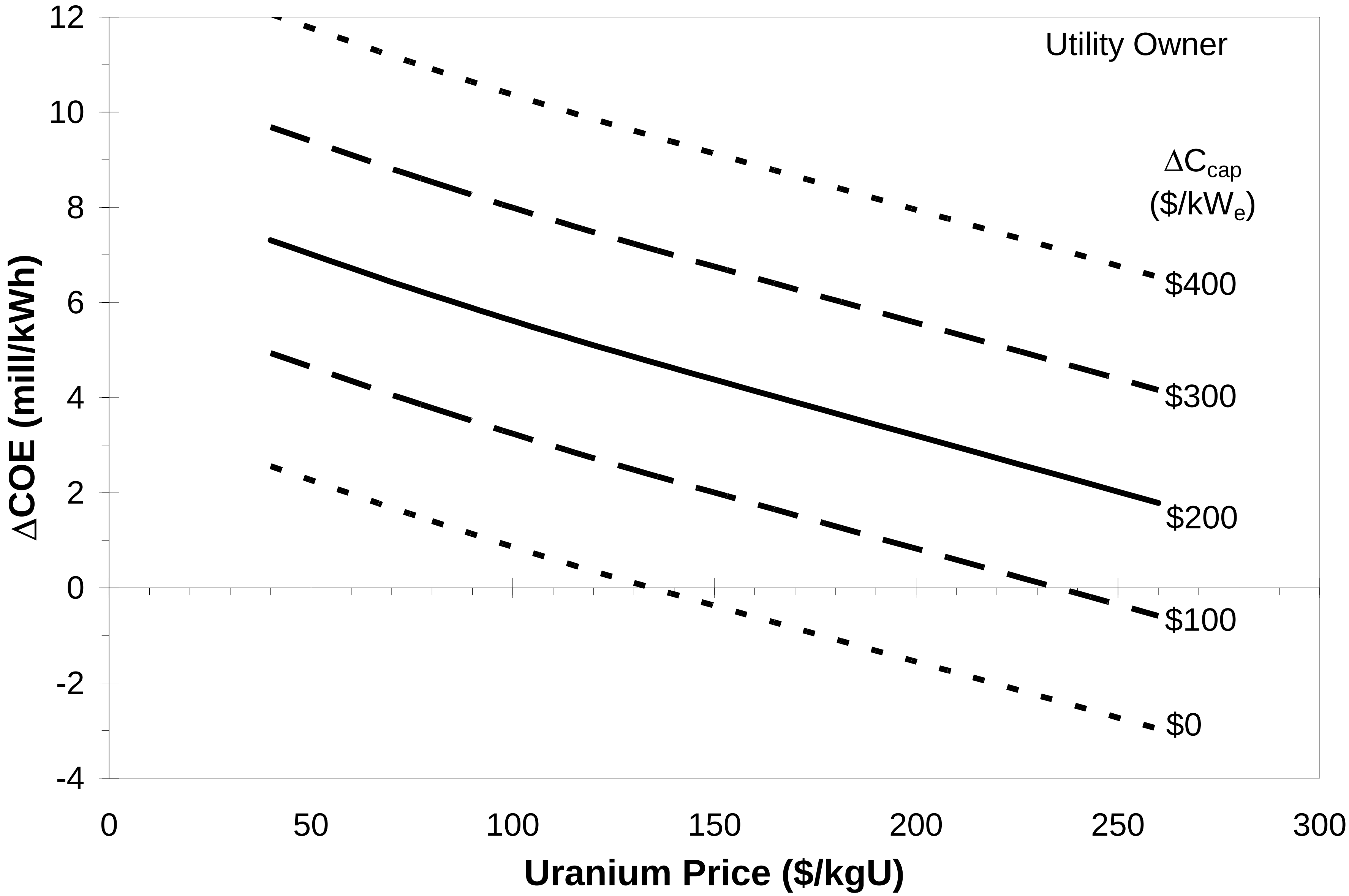
assuming regulated utility ownership

Parameter	**Break-even**	**best**	**central**	**worst**
Uranium ($/kg)	**340**		50	
Capital Cost Difference	**–95**	0	200	400
Reprocessing ($/kg)	**<0**	500	1000	2000
Interim fuel storage	**4100**	300	200	100
Disposal cost difference	**3400**	300	200	100
Enrichment ($/SWU)	**570**	150	100	50

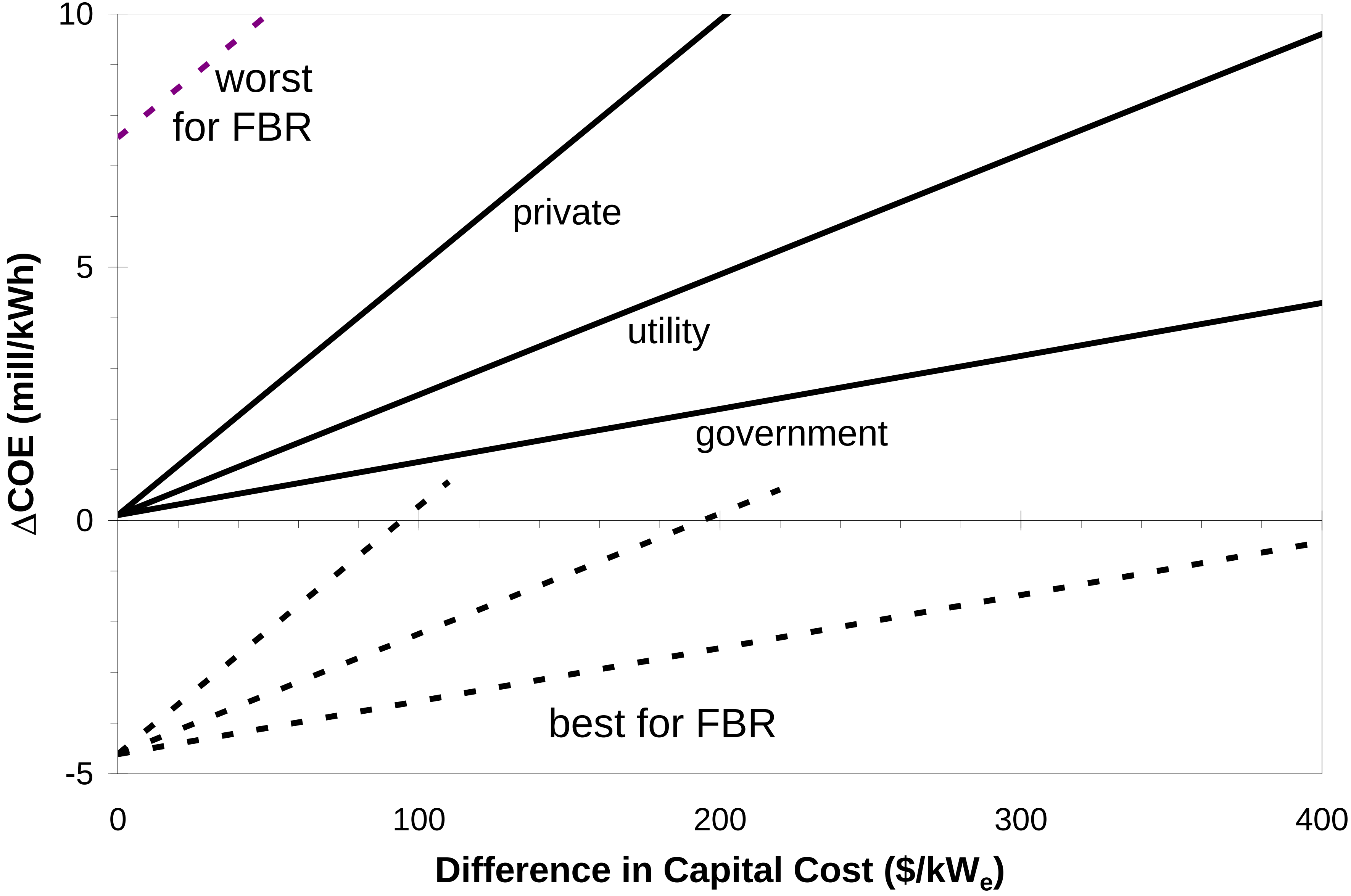
Breakeven U Price v. Capital Cost Difference



COE Premium for FBR



COE Premium for C_u = \$130/kg



Uranium Resources

- Breakeven U prices using central values:

  $340/kg (FBR) $370/kg (LWR)
- Breakeven U price > $130/kg even in best case
- How much is available? Red Book gives 16 Mt available at $130/kg or less, but…
  - high-cost resources in many countries (e.g., Australia) not estimated;
  - unconventional resources (e.g., phosphates) not included;
  - little investment in exploration

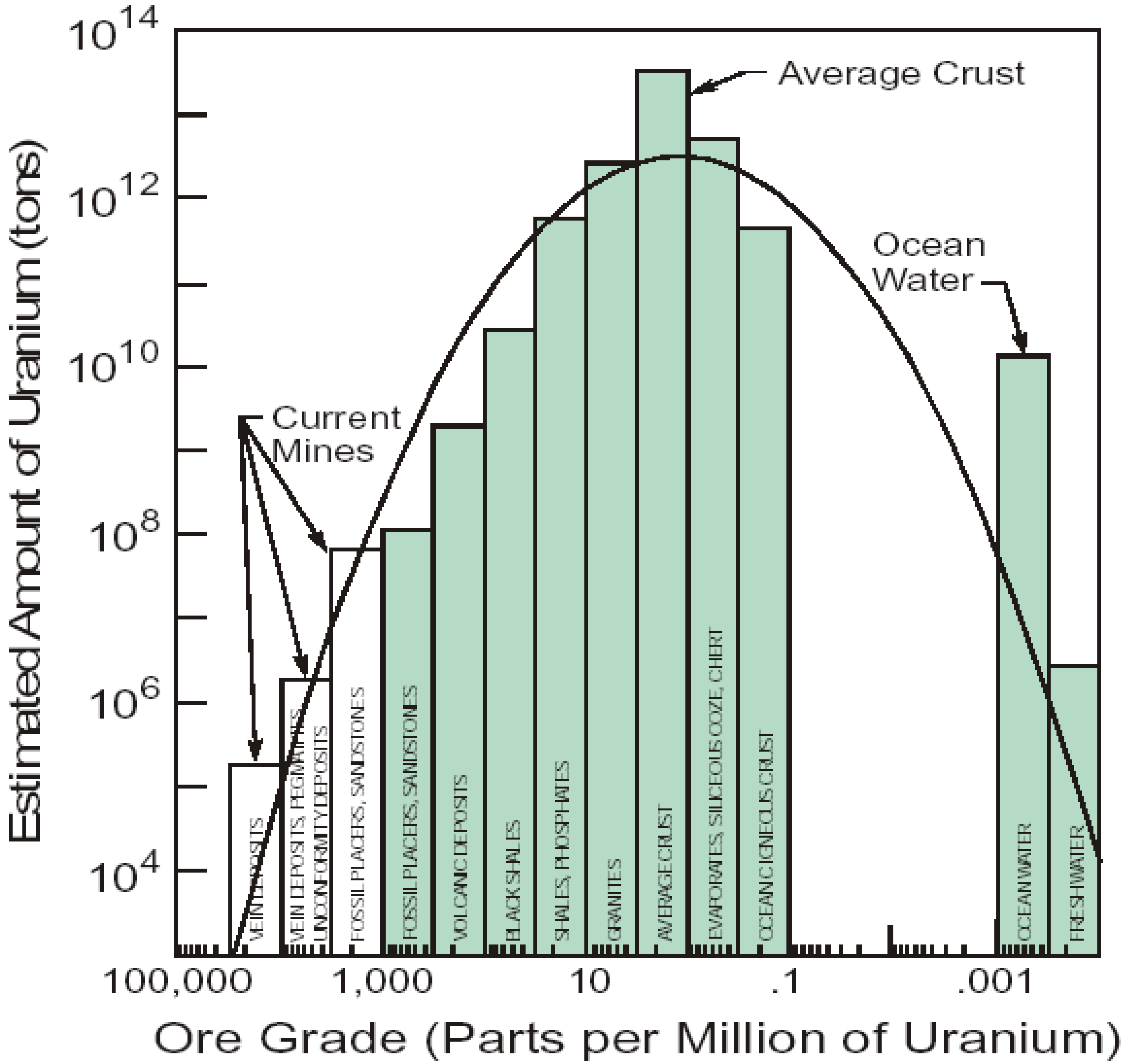
A Very Rough Estimate of Ultimately Recoverable Uranium Resources

- Red Book give 2.1 Mt at \$40/kg (~current price)
- Hore-Lacy: “a doubling of price from present levels could be expected to create a tenfold increase in measured resources.”
- So there should be 21 Mt available at \$80/kg and 210 Mt at \$160/kg

$$R = 2.1\left(\frac{p}{40}\right)^{\varepsilon}$$

ε = long-term price elasticity of supply

Deffeyes and MacGregor (1980)

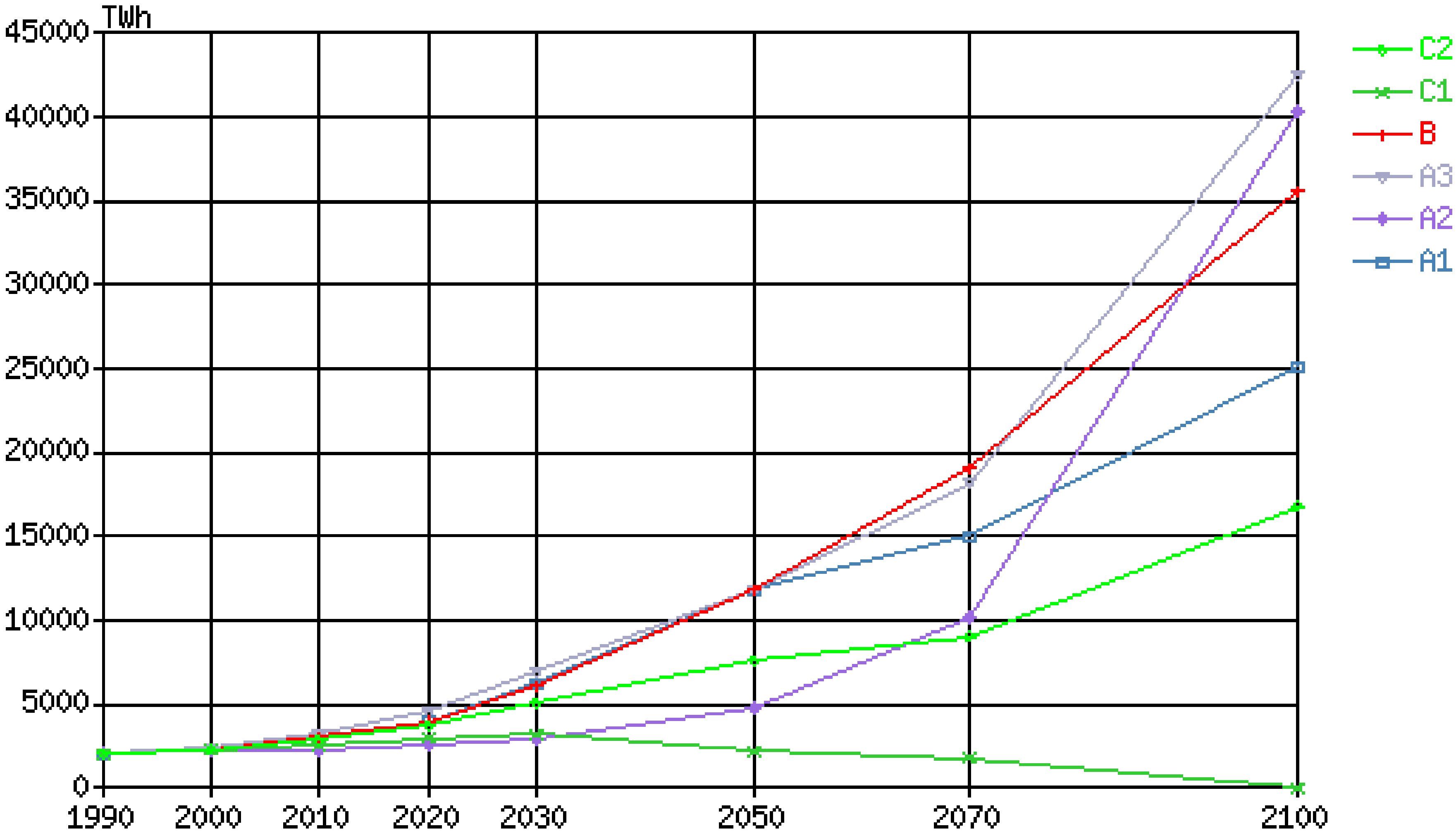


On average, a 10-fold decrease in ore grade is associated with a 300-fold increase in available resource

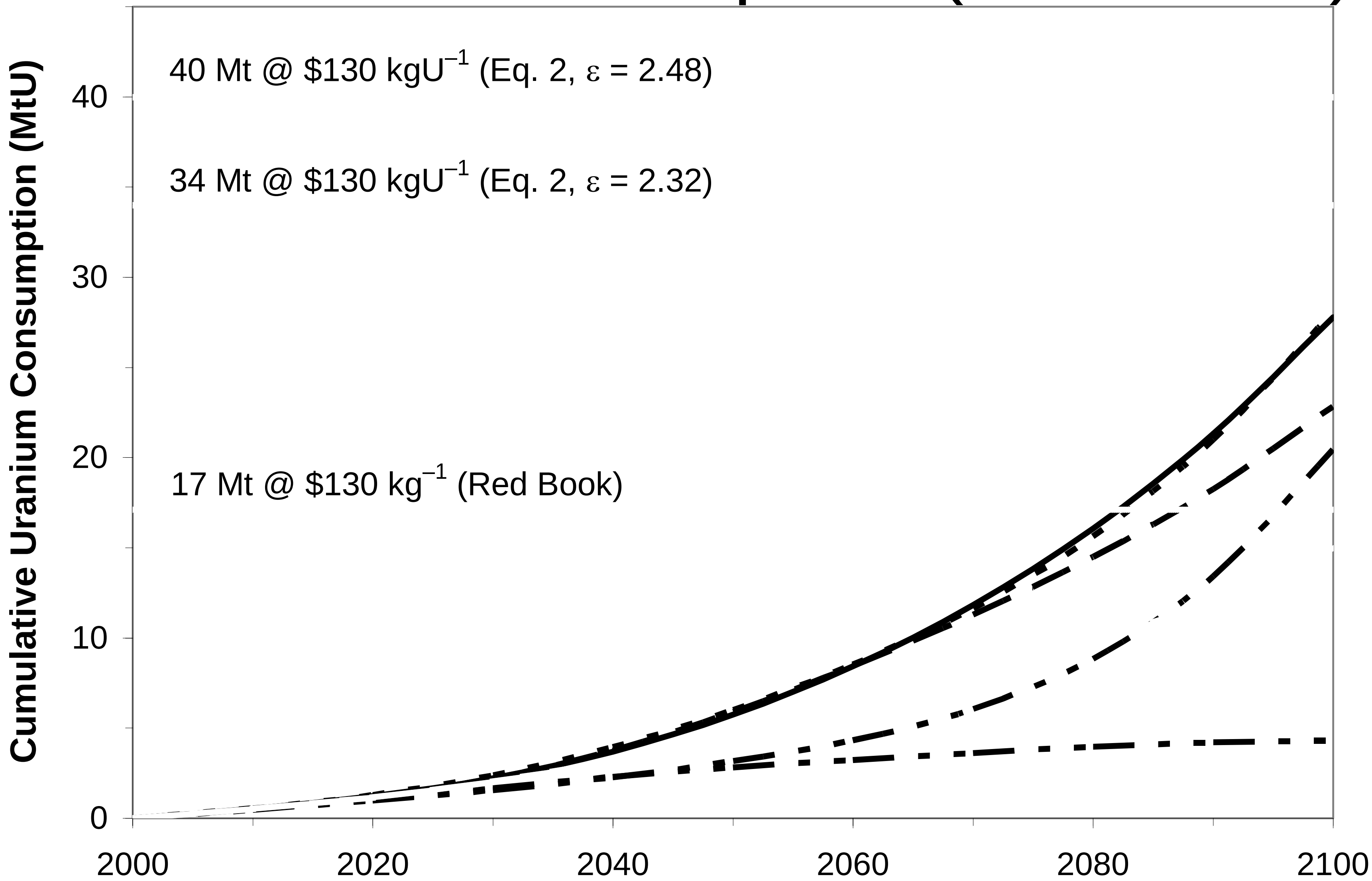
Recoverable Resources

Source	Long-term elasticity of supply 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

IIASA/WEC Global Energy Perspectives Nuclear Electricity Production Scenarios



Cumulative Uranium Consumption LWRs with Direct Disposal (19 tU/TWh)



Repository Space

- Can reprocessing substantially reduce need for new repositories?
- Recycle in LWRs: no
  - buildup of minor actinides increases decay heat per kWh
- Recycle in FRs with minor actinides : yes, but…
  - reprocessing, fabrication more expensive
    - Gen-IV: $2000/kg reprocessing, $2600/kg core fuel
    - if C_U = $130/kg:

      ΔCOE = 6 mill/kWh if ΔC_{cap} = $0

      16 mill/kWh if ΔC_{cap} = $200/kWh

Repository Space

- Repository space is scarce because of political barriers to new repositories, but
  - most countries can greatly expand repository capacity without new site (but not US)
  - some countries may accept foreign waste, given very high willingness to pay for service
  - political barriers to separation and transmutation are unlikely to be smaller than barriers to new repositories, especially given much greater near-term risks

Backup Slides

Calculating Breakeven Uranium Price

$$\begin{bmatrix} \text{cost of} \\ \text{direct-disposal} \end{bmatrix} = \begin{bmatrix} \text{cost of} \\ \text{reprocessing-recycle} \end{bmatrix}$$

$$\begin{bmatrix} \text{cost of interim storage} \\ \text{+ disposal of spent fuel} \end{bmatrix} = \begin{bmatrix} \text{cost of reprocessing} \\ \text{+ disposal of wastes} \end{bmatrix} - \begin{bmatrix} \text{value of} \\ \text{recovered} \\ \text{Pu + U} \end{bmatrix}$$

$$\begin{bmatrix} \text{value of} \\ \text{recovered Pu} \end{bmatrix} = \begin{bmatrix} \text{cost of LEU} \\ \text{using natural U} \end{bmatrix} - \begin{bmatrix} \text{cost of equivalent} \\ \text{MOX fuel} \end{bmatrix}$$

$$\begin{bmatrix} \text{value of} \\ \text{recovered U} \end{bmatrix} = \begin{bmatrix} \text{cost of LEU} \\ \text{using natural U} \end{bmatrix} - \begin{bmatrix} \text{cost of LEU} \\ \text{using recycled U} \end{bmatrix}$$

Simple Example

Direct Disposal	Cost ($\$/kg_{HM}$)
Interim storage of SF	\$200
Geologic disposal of SF	\$400
	\$600

Reprocessing-Recycle	
Reprocessing	\$1000
Geologic disposal of HLW, ILW	\$200
Recovered U (0.95 kg_U/kg_{HM})	$-0.95C_{rU}$
Recovered Pu (0.01 kg_{Pu}/kg_{HM})	$-0.01C_{Pu}$
	$\$1200 - 0.95C_{rU} - 0.01C_{Pu}$

Value of Plutonium

LEU Cost	Quantity	Unit Cost	Cost ($/kg)
Uranium	7 kg	C_U	$7C_U$
Conversion	7 kg	$6/kg	$42
Enrichment	6 SWU	$100/SWU	$600
Fabrication	1 kg	$250/kg	$250
			$892 + 7C_u$

MOX Cost			
DU	0.94 kg	$6/kg	$6
Plutonium	0.06 kg	C_{Pu}	$0.06C_{Pu}$
Fabrication	1 kg	$1500/kg	$1500
			$1506 + 0.06C_{Pu}$

If $C_{LEU} = C_{MOX}$: $$C_{Pu} = \frac{7C_U - 614}{0.06}$$

Breakeven U Price

$$\begin{bmatrix}\text{cost of interim storage} \\ \text{+ disposal of SF}\end{bmatrix} = \begin{bmatrix}\text{cost of reprocessing} \\ \text{+ disposal of wastes}\end{bmatrix} - \begin{bmatrix}\text{value of} \\ \text{Pu + rU}\end{bmatrix}$$

$$\frac{\$600}{kg_{HM}} = \frac{\$1200}{kg_{HM}} - 0.01C_{Pu} - 0.95\,C_{rU}$$

Assume
$C_{rU} \approx C_U$

$$\frac{\$600}{kg_{HM}} = \frac{\$1200}{kg_{HM}} - 0.01\left[\frac{7C_U - 614}{0.06}\right] - 0.95C_U$$

$$12.7\,C_U = 4214$$

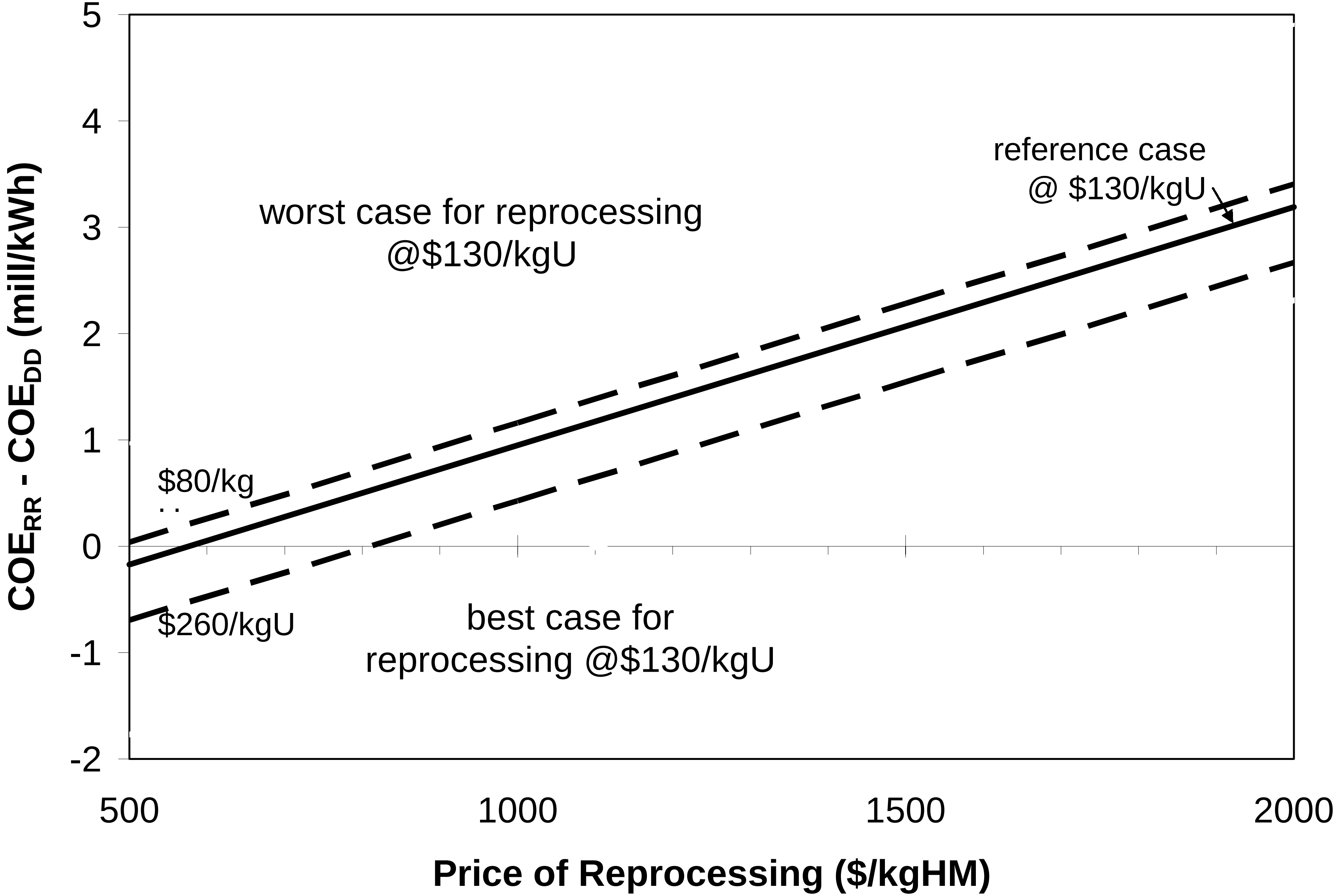
$$C_U = \frac{\$330}{kg}$$

A more precise calculation gives \$370/kg ~8 times the current spot price

Other Parameters

Parameter	**best**	**central**	**worst**
LEU fuel fabrication ($/kg)	350	250	150
Conversion ($/kg)	8	6	4
Spent-fuel burnup (MWd/kg)	33	43	43
Fresh-fuel burnup (MWd/kg)	53	43	43
Discount rate (%/y)	8	5	2
Laser enrichment	yes	no	no
Premiums for recovered U			
Conversion ($/kg)	5	15	25
Enrichment ($/SWU)	0	5	10
Fabrication ($/kg)	0	10	20

COE Premium for Reprocessing-Recycle



Reprocessing Cost

- Central value = $1000/kg (range: 500 to 2000)
  - includes SF transport; interim storage of SF, Pu, HLW; disposal of LLW; decommissioning
- Thorp, UP3:
  - baseload: $1700-2300/kg
  - post-baseload: $1000-1500 → $600-900/kg
- Rokkasho-Mura: $4000/kg
- Using reported Thorp capital, operating costs: $1350 (govt), $2000 (utility), $3100 (private)

MOX Fuel Fabrication

- Central value = $1500/kg (range: 700 to 2300)
  - no extra costs for fuel transport or use at reactors

- 1990s prices: $2100-2700/kg
- Using SMP reported capital and operating costs: $1000 (govt), $1500 (utility); $2100 (private)

Interim Spent-fuel Storage

- Central value = $200/kg (range: 100 to 300)
- Cost estimates:
  - at-reactor dry storage: $100-120/kg
  - dry storage at other sites: $150-200/kg
  - centralized facility, Japan: $280/kg
- IS would not be required at new reactors with lifetime storage capacity, or after opening of repository

Disposal Cost Difference

	Spent Fuel	**HLW**	**SF – HLW**	**% savings**
This study	400	200	200	50%
			100-300	25-75%
1993 OECD study	140	70	70	50%
2000 French study	130	80	50	40%
Gen IV study	300	200	100	33%

1 mill/kWh = $370/kg at discharge if burnup = 43 MWd/kg

Parameter	Parameter Value			Breakeven U price (central = $340/kgU)		change compared to central
	low	central	high	low	high	
Capital cost difference ($/kW$_e$)	0	200	400	134	560	–205 +221
Reactor owner	govt	utility	private	222	574	–118 +234
Reprocessing cost ($/kgHM)	500	1000	2000	255	516	–85 +176
Enrichment ($/SWU)	150	100	50	282	415	–58 +75
LMR core fabrication ($/kgHM)	700	1500	2300	286	394	±54
LMR breeding ratio	1.0	1.125	1.25	294	386	±46
Geological disposal cost difference ($/kgHM)	300	200	100	322	358	±18
LEU burnup (MW$_t$d/kgHM)	43	53	53	322	340	–17
Construction time (yr)	3	6	9	326	355	±15
LMR blanket fab. ($/kgHM)	150	250	350	325	355	±15
LEU fuel fabrication ($/kgHM)	350	250	150	327	353	±13

Uranium Prices