The Future of Nuclear Power

AN INTERDISCIPLINARY MIT STUDY

Interdisciplinary study group

Steve Ansolabehere (Political Science)
John Deutch (Chemistry)   (co-chair)
Mike Driscoll (Nuclear Engineering)
Paul Gray (Electrical Engineering)
John Holdren (Energy Systems)
Paul Joskow (Economics)
Richard Lester (Nuclear Engineering)
Ernie Moniz (Physics) (co-chair)
Neil Todreas (Nuclear Engineering)

The Context

- If atmospheric CO_2 concentration is not to exceed twice its pre-industrial value, 21st century CO_2 emissions will need to be held to half the cumulative total under 'business as usual' trajectory

  =>Annual emission rate in 2050 will need to have fallen back (roughly) to its level in 2000.

- This will be extremely difficult!

The Context

There are four basic options for reducing greenhouse gas emissions from electricity production:

- Increased efficiency in electricity supply and use
- Increased use of renewables
- Continued use of fossil fuels, coupled with carbon capture and sequestration
- More nuclear power

It would be a mistake to exclude any of the four options from an overall carbon emissions reduction strategy.

The Question

What must be done to make nuclear power a significant option for meeting increasing global electricity demand while reducing greenhouse gas emissions?

The Obstacles

- Economic competitiveness
- Concerns over nuclear safety
- Nuclear waste disposal
- Nuclear proliferation risks

The Global Growth Scenario

- 1000 GWe of nuclear capacity by 2050
  - Nearly 3x current nuclear capacity
  - Would avoid 25% of the increment in global carbon emissions expected in the business-as-usual case
    - 1.8 GT/yr of carbon emissions avoided if the nuclear capacity displaced coal
    - cf. 6 GT/yr of carbon emissions today
  - Would roughly maintain nuclear's current share of the global electricity market (17%--->19%)

Illustrative nuclear deployment in the global growth scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE 2000	2050
Total World	1,000	17%	19%
Developed world	625	23%	29%
U.S.	300		
Europe and Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWe-hrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

RETAINING THE NUCLEAR OPTION AT A MEANINGFUL LEVEL MEANS PLANNING FOR GROWTH.

Findings: Economics

- In deregulated markets, nuclear power is not now cost competitive with coal or gas.
- Plausible (but so far unproven) reductions in nuclear plant capital costs, O&M costs, and construction lead-time could reduce the gap, but not eliminate it.
- These reductions, if combined with policies internalizing the social cost of carbon emissions (e.g., carbon tax, ‘cap-and-trade’ system) could make nuclear power cost competitive.

Results of merchant plant cost model

Comparative Power Costs

CASE (Year 2002 $)	REAL LEVELIZED COST Cents/kWe-hr
Nuclear (LWR)	6.7
+ Reduce construction cost 25%	5.5
+ Reduce construction time 5 to 4 years	5.3
+ Further reduce O&M to 13 mills/kWe-hr	5.1
+ Reduce cost of capital to gas/coal	4.2
Pulverized Coal	4.2
CCGT[a] (low gas prices, $3.77/MCF)	3.8
CCGT (moderate gas prices, $4.42/MCF)	4.1
CCGT (high gas prices, $6.72/MCF)	5.6

a. Gas costs reflect real, levelized acquisition cost per thousand cubic feet (MCF) over the economic life of the project.

Power Costs with Carbon Taxes

CARBON TAX CASES LEVELIZED ELECTRICITY COST cents/kWe-hr	$50/tonne C	$100/tonne C	$200/tonne C
Coal	5.4	6.6	9.0
Gas (low)	4.3	4.8	5.9
Gas (moderate)	4.7	5.2	6.2
Gas (high)	6.1	6.7	7.7

BASE-CASE COSTING ASSUMPTIONS

Nuclear

Overnight cost:	$2000/kWe
O&M cost:	1.5 cents/kWh (includes fuel)
O&M real escalation rate:	1.0%/year
Construction period:	5 years
Capacity factor:	85%/75%

Financing:

- Equity: 15% nominal net of income taxes
- Debt: 8% nominal
- Inflation: 3%
- Income Tax rate (applied after expenses, interest and tax depreciation): 38%
- Equity: 50%
- Debt: 50%

Project economic life:	40 years/25 years

BASE-CASE COSTING ASSUMPTIONS

Coal

Overnight cost: $1300/kWe

Fuel Cost: $1.20/MMbtu

Real fuel cost escalation: 0.5% per year

Heat rate (bus bar): 9300 BTU/kIWh

Construction period: 4 years

Capacity factor: 85%/75%

Financing:

- Equity: 12% nominal net of income taxes
- Debt: 8% nominal
- Inflation: 3%
- Income Tax rate (applied after expenses, interest and tax depreciation): 38%
- Equity: 40%
- Debt: 60%

Project economic life: 40 years/25 years

BASE-CASE COSTING ASSUMPTIONS

Gas CCGT

Overnight cost:	$500/kWe
Initial fuel cost:	
Low: $3.50/MMbtu ($3.77/MMbtu real levelized over 40 years)	
Moderate: $3.50/MMbtu ($4.42/MMbtu real levelized over 40 years)	
High: $4.50/MMbtu ($6.72/MMbtu real levelized over 40 years)	
Real fuel cost escalation:	
Low: 0.5% per year	
Moderate: 1.5% per year	
High: 2.5% per year	
Heat rate:	7200 BTU/kWh
Advanced:	6400 BTU/kWh
Construction period:	2 years
Capacity factor:	85%/75%
Financing:	
Equity: 12% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 40%	
Debt: 60%	
Project economic life:	40 years/25 years

Table 5.1 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (85% capacity factor)

Base Case	25-YEAR	40-YEAR
Nuclear	7.0	6.7
Coal	4.4	4.2
Gas (low)	3.8	3.8
Gas (moderate)	4.1	4.1
Gas (high)	5.3	5.6
Gas (high) Advanced	4.9	5.1
Reduce Nuclear Costs Cases		
Reduce construction costs (25%).	5.8	5.5
Reduce construction time by 12 months	5.6	5.3
Reduce cost of capital to be equivalent to coal and gas	4.7	4.4

Carbon Tax Cases (25/40 year)

	$50/tC	$100/tC	$200/tC
Coal	5.6/5.4	6.8/6.6	9.2/9.0
Gas (low)	4.3/4.3	4.9/4.8	5.9/5.9
Gas (moderate)	4.6/4.7	5.1/5.2	6.2/6.2
Gas (high)	5.8/6.1	6.4/6.7	7.4/7.7
Gas (high) advanced	5.3/5.6	5.8/6.0	6.7/7.0

Base
40 year life
85% CF

Nuclear Base

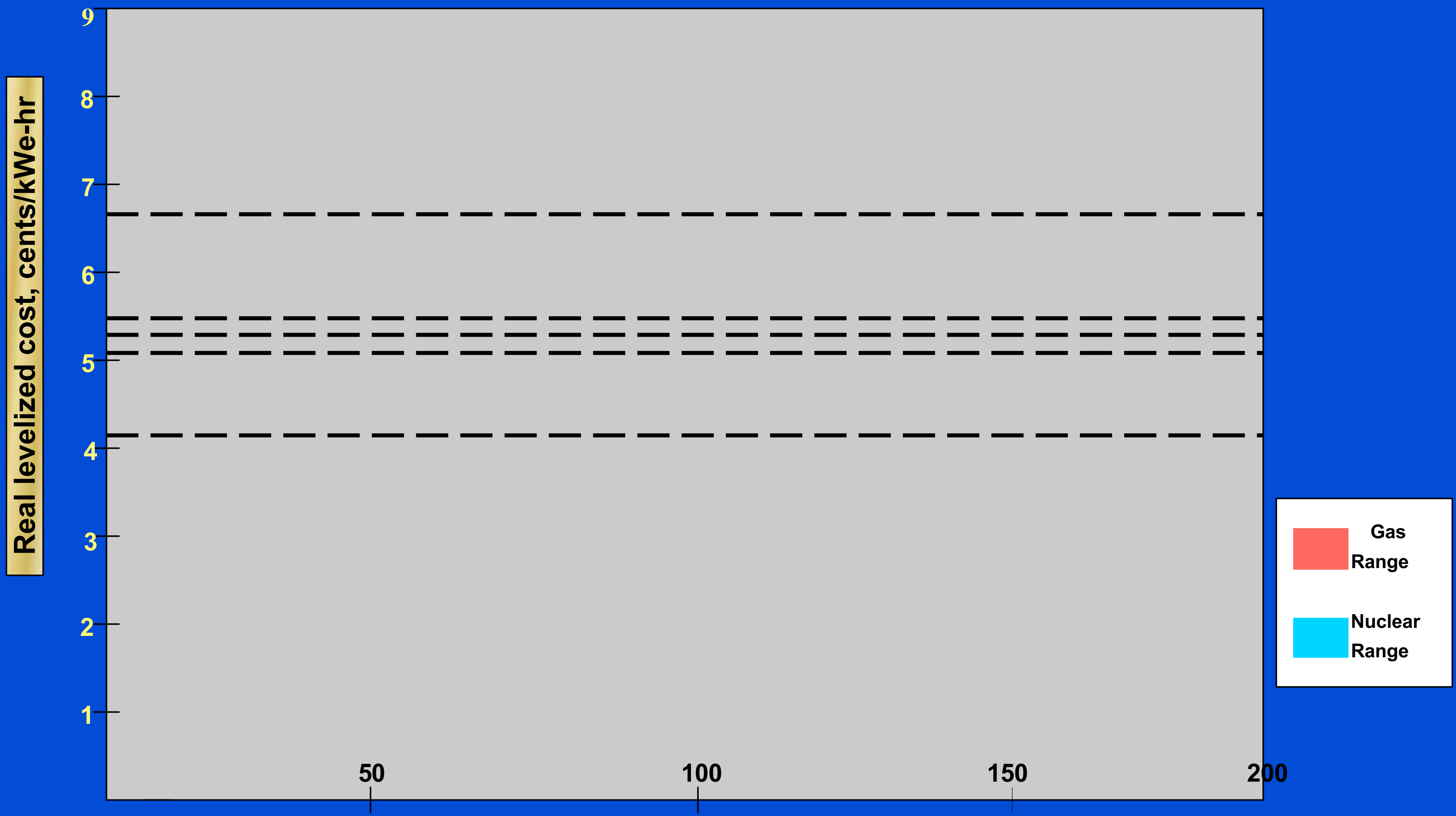
$2000/kW overnight

Reduce Construction Cost 25% → Reduce Construction Times from 5 to 4 years →

1.5¢/kWh (includes fuel)

Reduce O+M to 1.3¢ → Reduce cost of Capital to gas/coal

	Nuclear	Gas
Equity/Debt	50/50%	40/60%
Equity (nominal net of name tax)	15%	12%
Debt (Nominal)	8%	8%
Inflation	3%	3%
Income Tax Rate (after expenses, interest + tax depreciation)	38%	38%



Carbon Tax, $/tonne C

Base
40 year life
85% CF

Nuclear Base

$2000/kW overnight

Reduce Construction Cost 25% → Reduce Construction Times from 5 to 4 years →

1.5¢/kWh (includes fuel)

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	Nuclear	Gas
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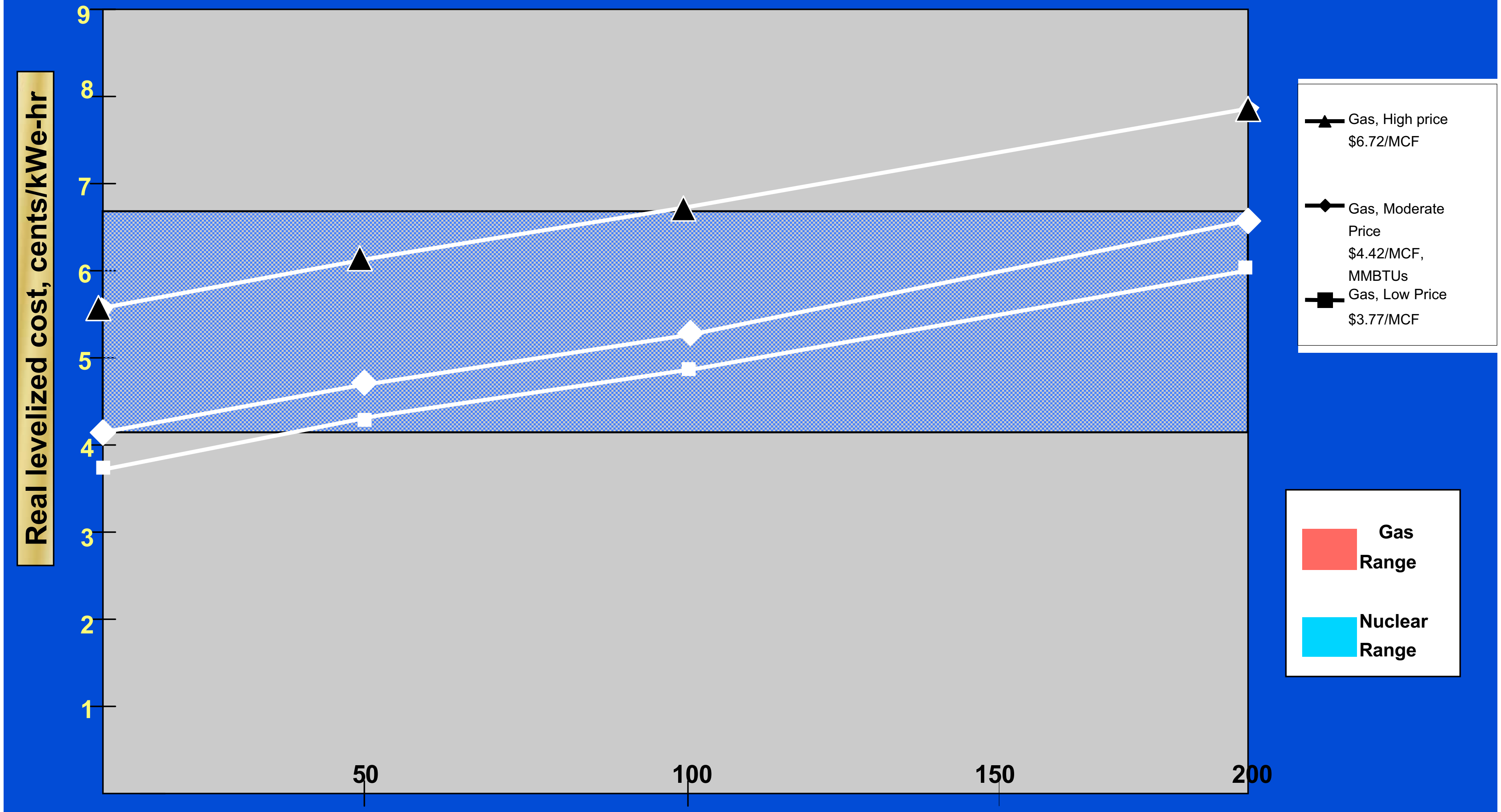


Findings: Safety

- Feasibility of global growth scenario will depend on maintaining a safety standard of < 1 accident resulting in a serious release of radioactivity over the next 50 years from all fuel cycle activity.

- Implies a ten-fold reduction in expected frequency of serious reactor core accidents.

- Achievable with advanced LWR technology + other designs.

- 'Best practices' in construction and operation are essential.

SAFETY (Contd.)

- Historical frequency of core-damage accidents in US commercial reactor operations = 1 in 3,000 reactor-years.
- Estimated frequency of core-damage accidents in current US commercial reactor fleet = 1 in 10,000 reactor-years.
- Core-damage accidents expected worldwide 2003-2050 in the study scenario if the latter estimate applies = 4.
- Claimed core-damage-accident frequency for advanced light-water-reactor designs = 1 in 100,000 reactor-years.
- Core-damage accidents expected worldwide 2003-2050 in the study scenario if this lower estimate applies = 0.4.

Findings: Waste management

- Geologic disposal is technically feasible but execution is yet to be demonstrated or certain.

- A convincing case has not been made that the long-term waste management benefits of advanced, closed fuel cycles involving spent fuel reprocessing and partitioning and transmutation of the minor actinides are outweighed by the short-term risks and economic costs.

Figure 7.3 Radiotoxicity Index for 1MT of Spent Fuel

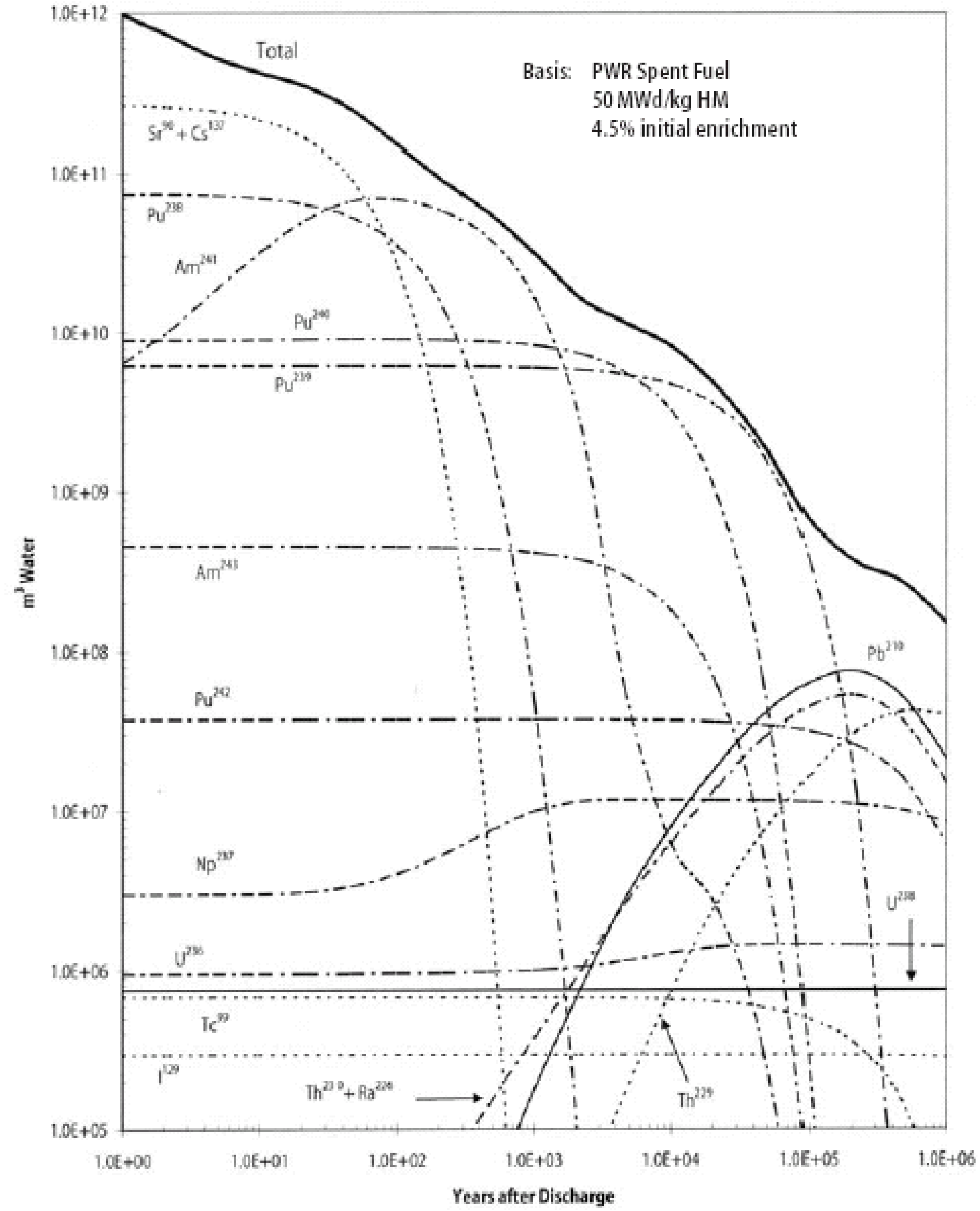


Figure 7.2 Decay Heat Profile of Spent Fuel

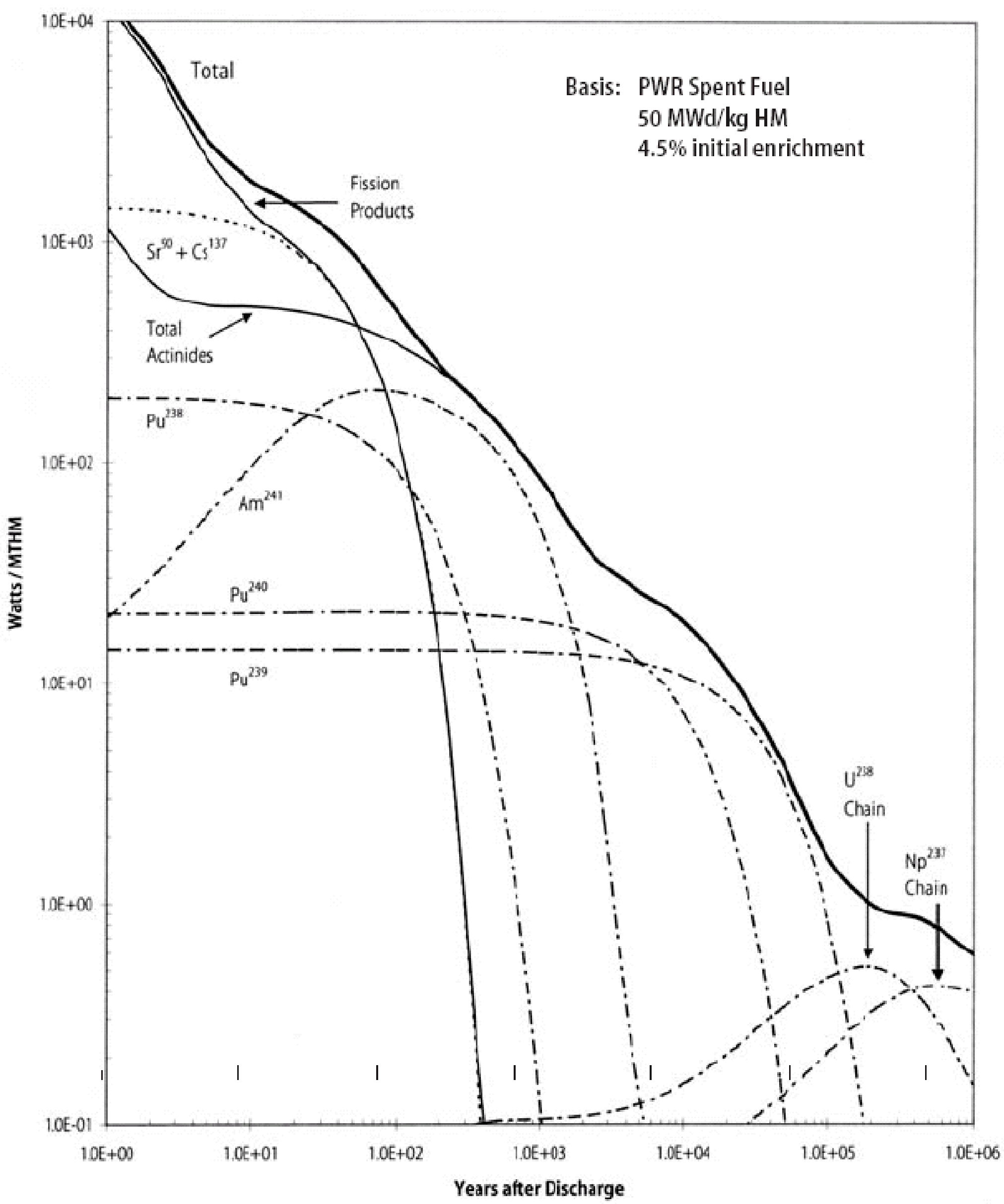


Figure 4.1 Open Fuel Cycle: Once-Through Fuel — Projected to 2050

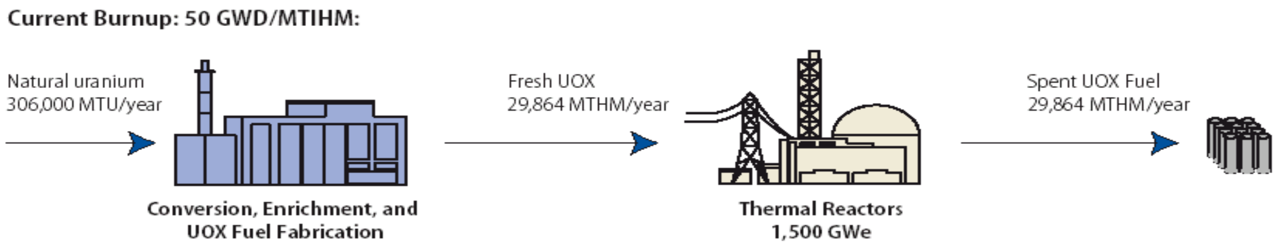
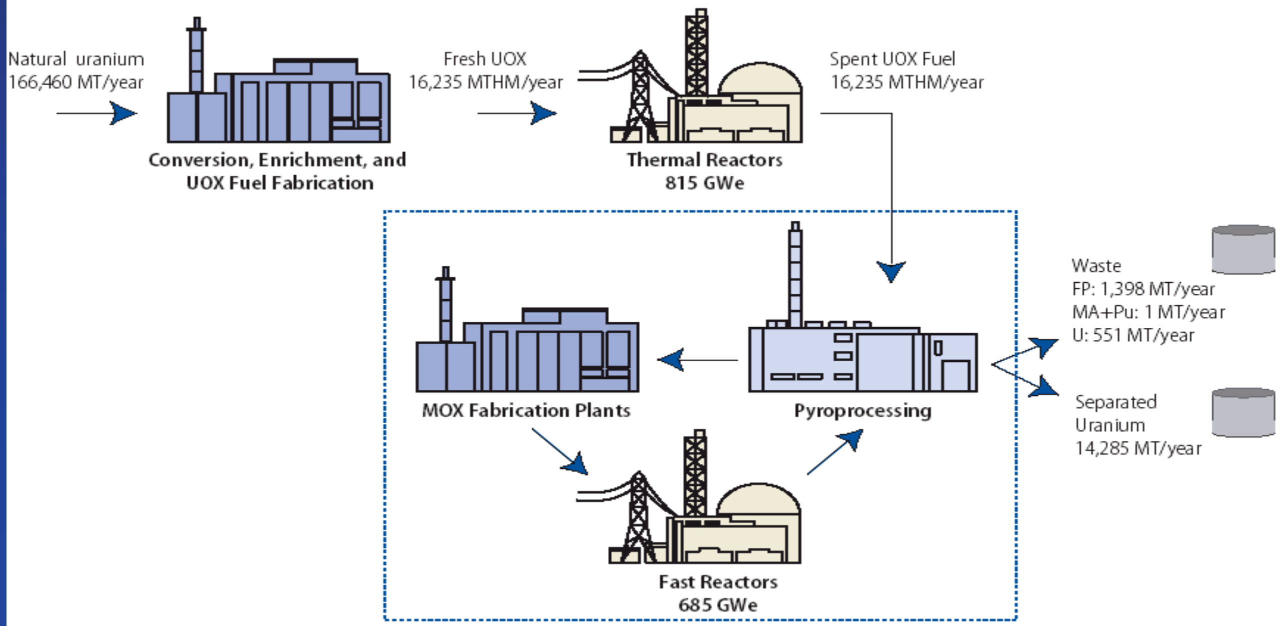


Figure 4.3 Closed Fuel Cycle: Full Actinide Recycle — Projected to 2050



Findings: Waste management

- Geologic disposal is technically feasible but execution is yet to be demonstrated or certain.

- A convincing case has not been made that the long-term waste management benefits of advanced, closed fuel cycles involving spent fuel reprocessing and partitioning and transmutation of the minor actinides are outweighed by the short-term risks and economic costs.
  - Technological advances may change this assessment
  - But for the basic conclusion to change, long term risks from geologic repositories would have to be much <u>higher</u> than the performance assessments currently suggest, <u>and</u> incremental costs and short-term risks of partitioning and transmutation would have to be much <u>lower</u> than current analyses indicate.

- Advances in the open, once-through fuel cycle potentially offer waste management benefits at least as large as those claimed for the more expensive closed fuel cycles.

Findings: Proliferation

- Nuclear power can expand as envisioned in a global growth scenario with acceptable incremental proliferation risk, if built primarily on the once-through thermal reactor fuel cycle and if combined with strong safeguards and security measures.

- The current international safeguards regime is not adequate to meet the security challenges implied by a global growth scenario and requires serious reexamination by the international community.

A key conclusion

"Over at least the next 50 years, the best choice to meet these challenges [economic, safety, waste, proliferation] is the open, once-through fuel cycle. . . .

. . . We judge that there are adequate uranium resources available at reasonable cost to support this choice under a global growth scenario."

Uranium Resource

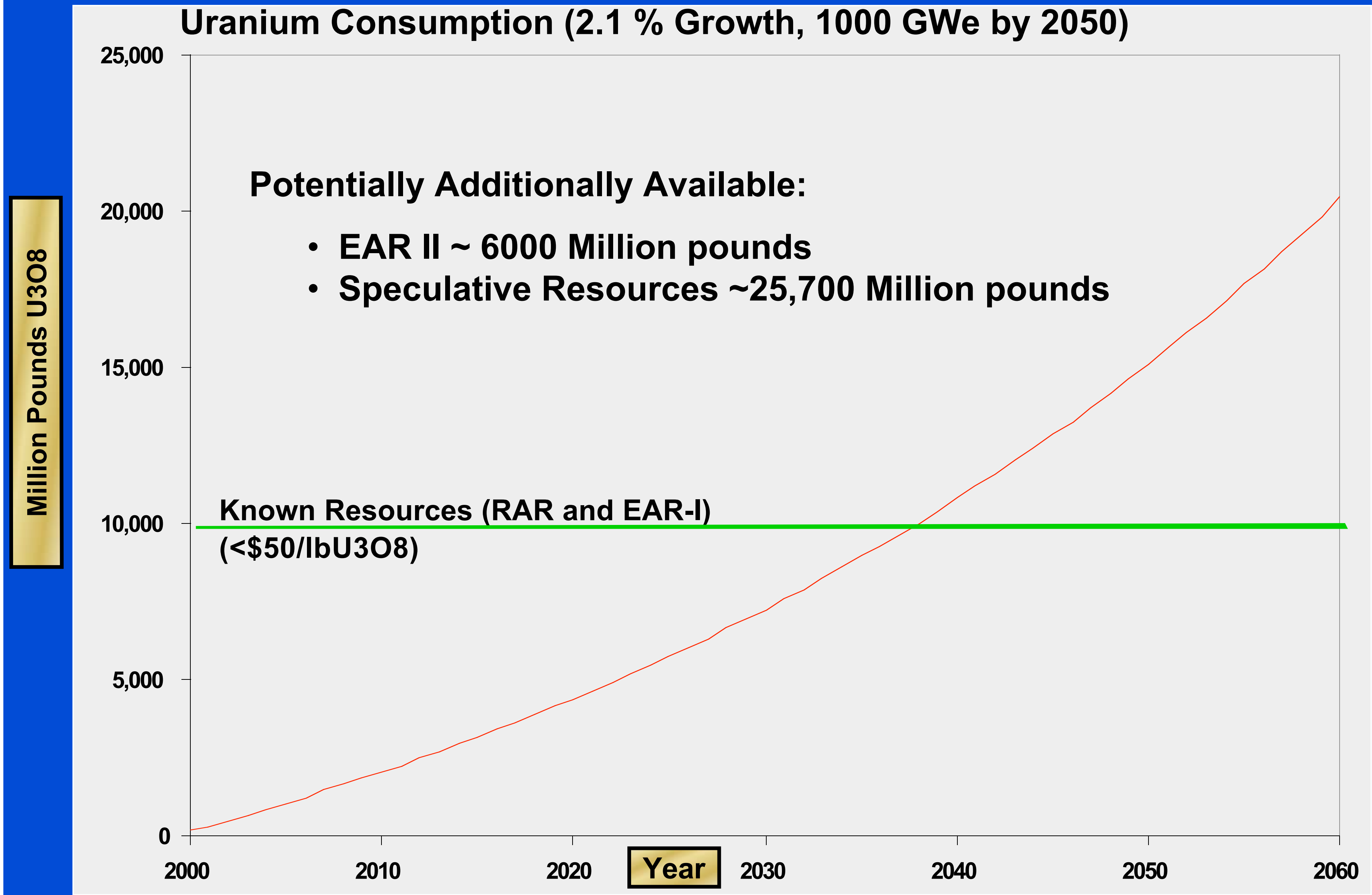


Figure A-5.E.2 Composite mineral price index for 12 selected minerals, 1900 to 1998, in constant 1997 dollars. Selected mineral commodities include 5 metals (copper, gold, iron ore, lead, and zinc) and seven industrial mineral commodities (cement, clay, crushed stone, lime, phosphate rock, salt, and sand and gravel).

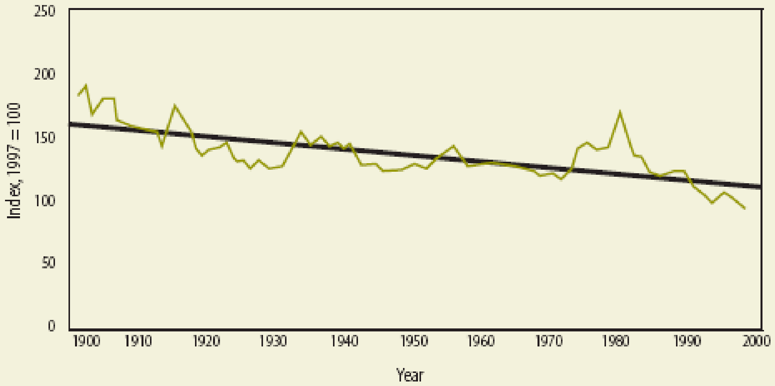


Table A-5.E.3 20th Century World Production and Price for 4 Selected Commodities

COMMODITY	PERIOD	INCREASE IN PRODUCTION (percent)	DECREASE IN CONSTANT DOLLAR PRICE (percent)
Aluminum	1900–1998	3,250	89.7
Copper	1900–1998	2,465	75.0
Potash	1919–1998	3,770	93.9
Sulfur	1907–1998	6,000	89.4

A further finding

Public acceptance is critical to the expansion of nuclear power. In the United States, the public does not currently see nuclear power as a way to address global warming.

PUBLIC PERCEPTIONS: THE MIT SURVEY

- Performed by Knowledge Networks, which drew a random sample of 1800 people from its "panel", of whom 1358 completed the survey.
- All respondents were 18 years or over, with a median age around 45.
- Of the respondents, 31% had completed only high school, 28% had some college, and 24% had a bachelor's degree or higher.
- Three fourths were white, 62% were married, 52% were female.

Question 11: To make more electricity to meet the country's needs over the next 25 years, new power plants will have to be built. Companies and government agencies need to start planning today. How should we meet this demand?

DISTRIBUTION OF RESPONSES (all groups):

FUEL	NOT USE	REDUCE A LOT	REDUCE SOMEWHAT	KEEP SAME	INCREASE SOMEWHAT	INCREASE A LOT
Coal	4.8%	23.3	29.9	25.0	10.7	6.0
Dams	1.4	3.8	11.2	31.1	34.2	18.0
Gas	1.3	6.3	24.1	37.2	22.7	8.1
Nuclear	9.2	19.2	18.6	24.6	18.3	9.8
Oil	3.4	19.7	33.6	30.2	9.5	3.2
Solar	1.4	2.3	4.9	13.6	27.0	50.4
Wind	1.6	2.5	4.7	13.9	24.4	52.6

Question 9. There are approximately 100 nuclear power plants in the United States. How likely do you think it is that in the next 10 years there will be a serious accident at a nuclear power plant?

Almost Certain	18.9%
Very Likely	23.0
Somewhat Likely	31.9
Not Very Likely	23.6
Not At All	2.3

Question 10. Do you agree or disagree with the following: Nuclear waste can be stored safely for many years.

Strongly Agree	5.9%
Agree	30.3
Disagree	39.7
Strongly Disagree	23.9

Surprising survey result

- The public's view about global warming doesn't predict attitudes towards nuclear power
  - There is no significant difference in the degree of support for nuclear power between those who are concerned about global warming and those who aren't
  - I.e., the carbon-free character of nuclear power doesn't appear to motivate the U.S. public to favor expansion of the nuclear option

Selected policy recommendations: economic competitiveness

- The U.S. government should provide production tax credits for a set of 'first mover' nuclear power plants
  - 1.7 cents/kwh up to $200/kwe for up to 10 plants
  - ~ 1.5 years of full power operation
  - Equivalent to $70 per avoided tonne of carbon emissions from coal plants ($160 per tonne for gas) -- but only for first 1.5 yrs.
  - Production tax credit mechanism offers greatest incentive for projects to be completed
    - If the plant isn't completed and operated, there is no subsidy

Selected policy recommendations: waste management

- Long-term storage of spent fuel for several decades should become an integral part of the waste management system architecture
  - a network of centralized storage facilities should be established in the U.S. and internationally.
- The scope of waste management R&D should be significantly broadened
  - Should include an extensive program on deep borehole disposal

ON EXTENDED INTERIM STORAGE OF WASTE

Several decades of engineered interim storage would…

-- provide greater flexibility in the event of delays in repository development; allow a deliberate approach to disposal and create opportunities to benefit from future advances in relevant science and technology;

-- provide greater logistical flexibility, with centralized buffer storage capacity facilitating the balancing of short and long-term storage requirements, and enabling the optimization of logistics, pre- processing, and packaging operations;

-- allow countries that want to keep open the option to reprocess their spent fuel to do so without actually having to reprocess;

-- create additional flexibility in repository design, since the spent fuel would be older and cooler at the time of emplacement in the repository; and potentially reduce the total number of repositories required.

Selected policy recommendations: proliferation

- The international safeguards regime should be strengthened
  - Implement the Additional Protocol
  - Supplement accounting/inspection regime with continuous materials protection, control and accounting using surveillance and containment systems
  - Allocate safeguards resources in a risk-based framework keyed to fuel cycle activity
  - IAEA should focus overwhelmingly on safeguards and safety
- Reconsideration of NPT/Atoms for Peace/IAEA safeguards framework as it pertains to nuclear fuel cycle development

Selected policy recommendations: Analysis, research, development & demonstration

- The U.S. DOE should establish a Nuclear Systems Modeling Project to carry out the analysis, research, simulation and collection of engineering data needed to evaluate all fuel cycles from the viewpoint of cost, safety, waste management, and proliferation resistance
  - Models should be based on real engineering data
  - Development of advanced nuclear technologies -- either fast reactors or advanced fuel cycles employing reprocessing -- should await the results of the project
  - Modest laboratory-scale research and analysis on new separation methods and fuel forms
  - Only encompass technology pathways that do not produce weapons-usable material during normal operation
  - Overall ARD&D program will require ~ $400M/yr for 10 years