The Advanced Fuel Cycle and the US Spent Nuclear Fuel Legacy

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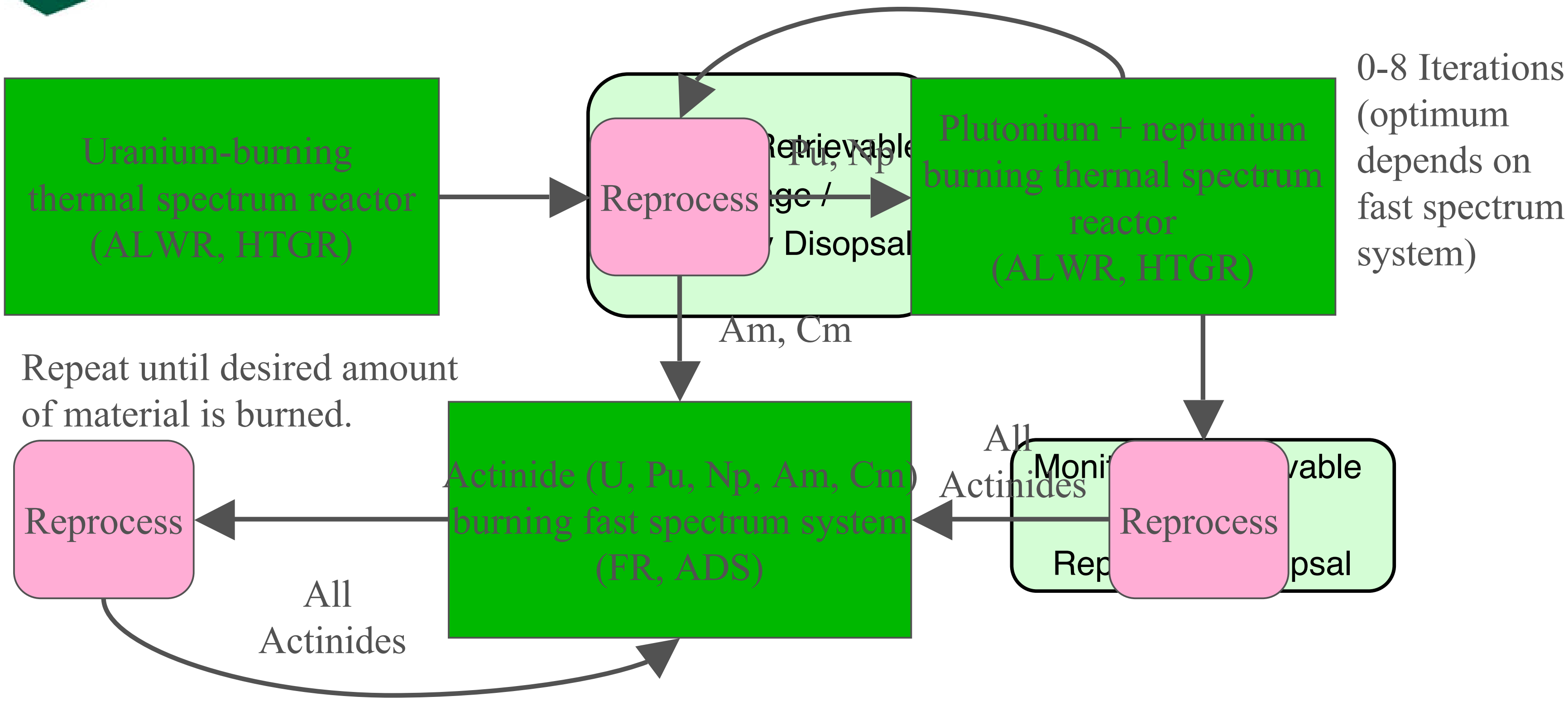
Introduction: Advanced Nuclear Fuel Cycles

There is no single advanced fuel cycle. Rather, all strategies that fall into this category share the property that they close the loop for actinide materials.

This is done through reprocessing of spent nuclear fuel and reintroduction of the recovered actinides into the fuel cycle. The objective is ultimately the transmutation of, and recovery of useful energy from, all actinide materials.

Building Blocks of an Advanced (Transmuting, Recycling) Fuel Cycle



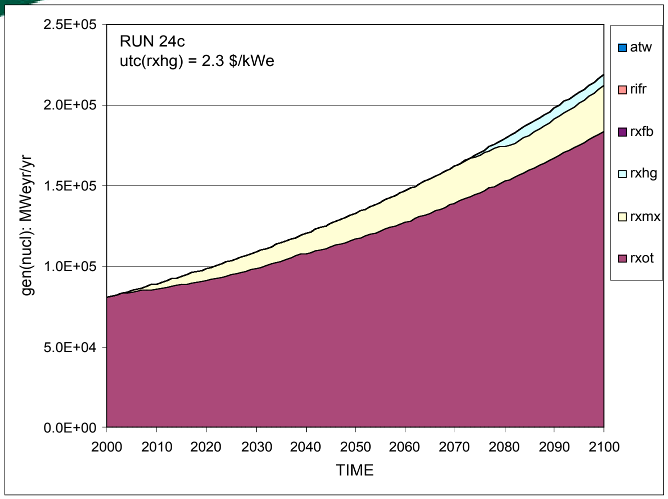
Each ‘pass’ through a Pu+Np burning system burns ~ 25% of the initial Pu+Np.
Each ‘pass’ through a fast spectrum system burns ~20% of all actinides.
Fast spectrum systems accept more feed per unit energy produced, but thermal spectrum systems are expected to be less expensive and more quickly available.

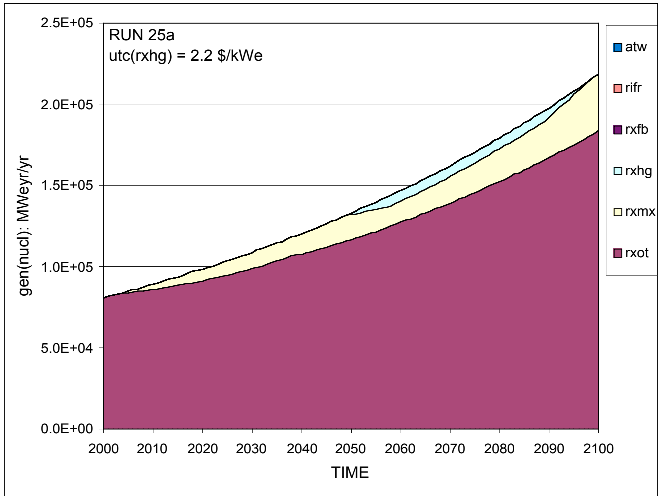
Why Transmute? Resource Availability is Not a Short Term Driver

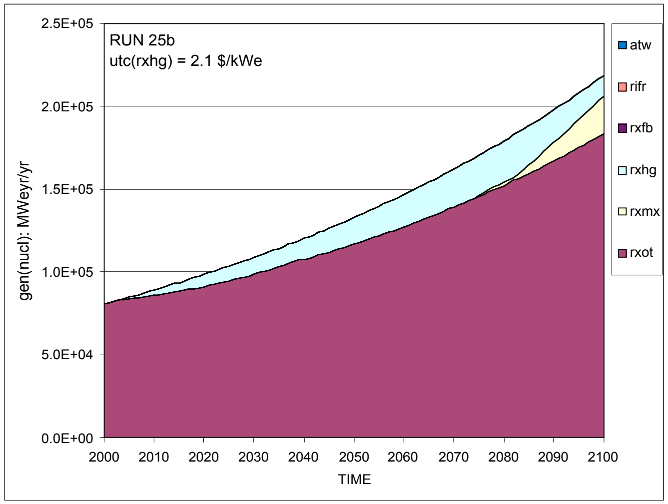
- Even discounting future discoveries, the uranium resource base as documented in the Redbook can support ~ 100 TW-yr of future once-through generation.
- Even under aggressive growth, this would suffice through midcentury
- The COE is not highly sensitive to uranium price shifts: a tenfold increase in resource price (from $30 to $300 per kg of natural uranium) would increase the cost of nuclear electricity by ~ 6 mills/kWh
- A sevenfold increase in uranium price would make re-enrichment of depleted uranium (currently stripped to 0.3% in the US) economically attractive, resulting in a 50% increase in the resource base

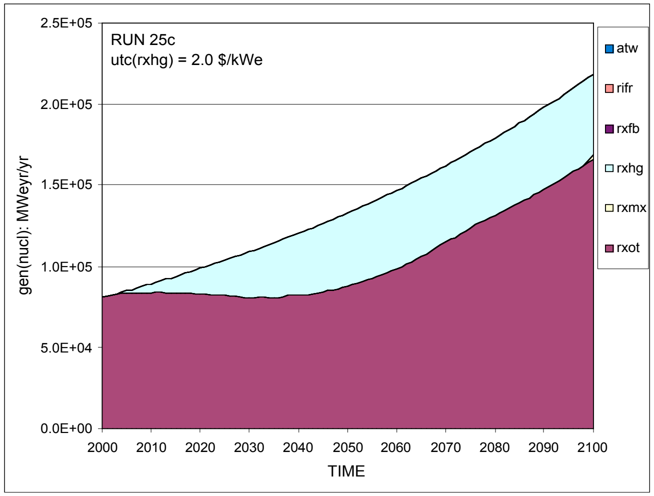
Taken together, these considerations imply that market forces would preclude the entry of breeders or transmuters for the next half century at a minimum.

Using Present-Day Cost Estimates, the Resource Burden is Alleviated Without Fast-Spectrum Systems









Time-dependent generation mixes:

once-through

LWR-MOX

HTGR

Why Transmute? The Spent Fuel Legacy in the US

A typical 1000 MWe nuclear power plant requires roughly 30,000 kgIHM (kilograms of initial heavy metal, e.g. uranium and plutonium) of fresh fuel per year.

Only a tiny fraction of this mass is converted through fission to energy, so the plant will discharge about the same amount of spent fuel each year.

This used fuel, of which there is currently 40,000 metric tons, constitutes the 'spent fuel legacy'.

In perspective:

Waste is a ubiquitous byproduct of electricity generation: each year,

10 grams of uranium is fissioned for a residential consumer of nuclear electricity.

1.6 tons of coal is burned for a residential consumer of coal electricity.

Current Plans for Spent Fuel Disposal

US spent fuel is currently slated to be emplaced in an engineered geological repository: Yucca Mountain, Nevada.

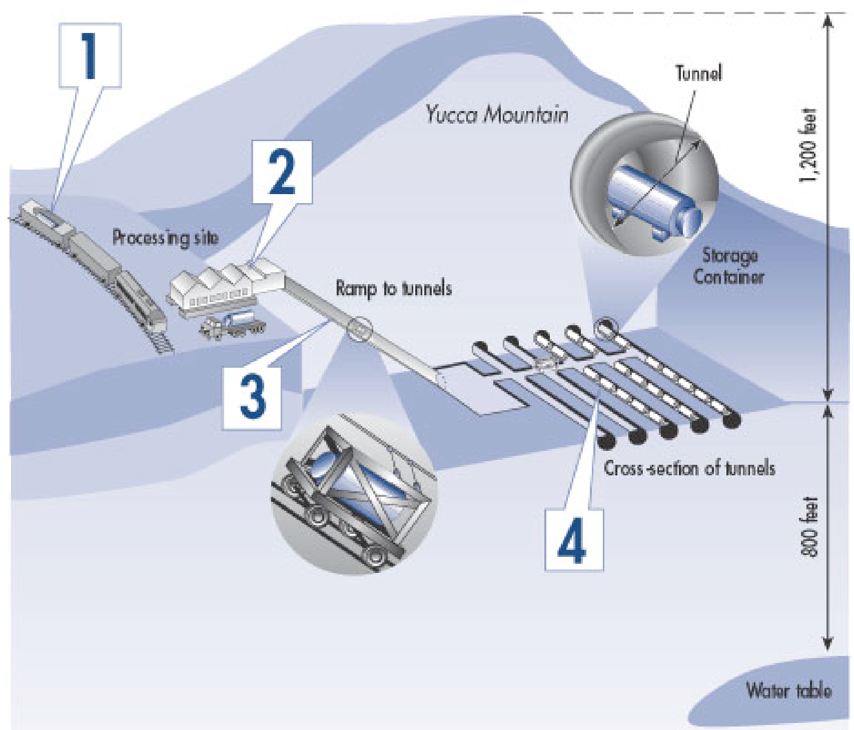
The repository has a legislated capacity of 63,000 tonsIHM of spent fuel.

Engineering factors affecting capacity include the waste's heat production rate and radiotoxicity:

- a major design objective is to limit dose to a maximally exposed member of the public to 15 mrem/year;
- this dose criterion must be satisfied for a 10,000 year period.

The LCC of the Yucca Mountain project is estimated by DOE at $42 – 57 bn [1]:

- this corresponds to roughly 1.4 mills/kWh of nuclear electricity generated.



Source: NRC

Yucca Mountain Does Not Solve the Problem Posed by Our Spent Fuel Legacy

Under a nuclear phaseout, each of the current US fleet of 104 reactors is retired when its licensed period of operation (typically 60 years) expires, and no new capacity is built.

Even this scenario would result in the production of ~ 120,000 tonIHM of SNF, leading to the need for a second repository.

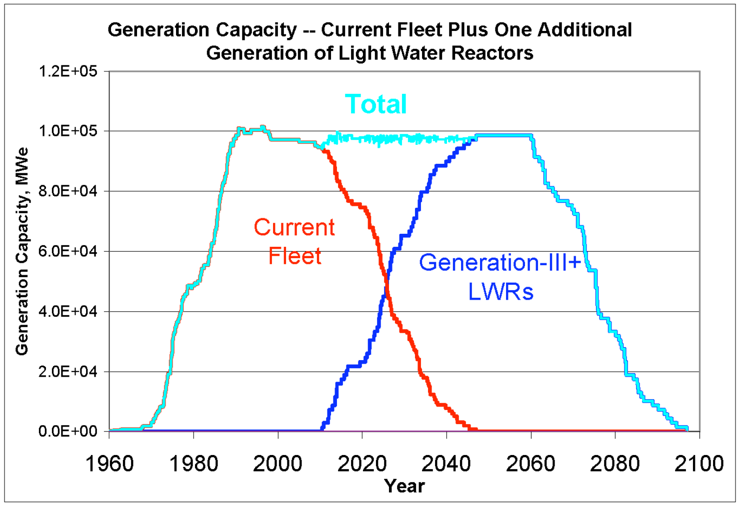
Additionally, hazardous materials would remain in the SNF:

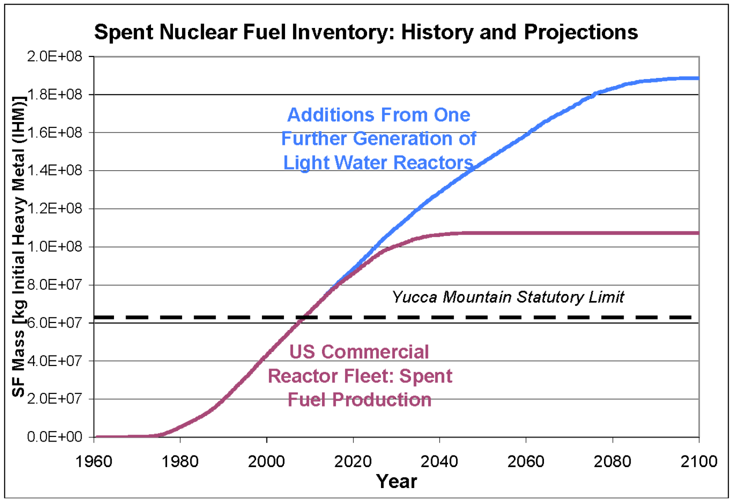
- Each kilogram of nuclear fuel, when burned, produces roughly 10 grams of plutonium and 1 gram of other actinide elements (the so-called minor actinides (MA), predominantly Np, Am and Cm).
- These actinides pose a significant radiotoxicity hazard: 1 kg of reactor-grade Pu, for instance, is a factor of 10^4 more hazardous (as measured by whole-body dose in rem) than natural uranium.
- Proliferation concerns also argue for special attention to be paid to these materials.

Yucca Mountain and Its Successor(s): A Need For Action

The Problem. The current US commercial nuclear fleet consists of 103 reactors. If these reactors operate until the expiration of their current operating licenses, their spent fuel will, if exceed the legislated capacity of the Yucca Mountain repository – 63,000 metric tons of fuel – by a factor of nearly 2.
This will occur even if no new facilities are built.

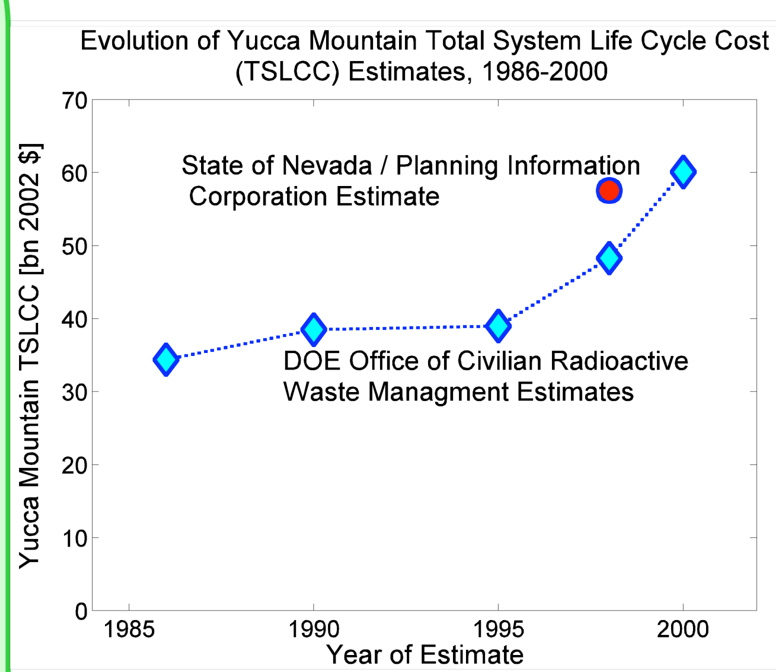
If, as seems possible given the loan guarantees for 6 new plants proposed by Senator Pete Domenici in June, 2003, a nuclear generation capacity roughly equivalent to today's 97 GWe is maintained through deployment of one further generation of Advanced Light Water Reactors (ALWRs), the issue by mid-century might become the necessity for not merely a second repository equivalent in capacity to Yucca Mountain, but also a third or even a fourth.





Uncertainties Associated with Yucca Mountain: A Risk Barrier to Market Entry

Why have no new nuclear power plants been ordered in the United States since 1978? A major part of the answer is *uncertainty associated with waste disposal*. Although the Federal Government, through the 1982 Nuclear Waste Policy Act, has guaranteed utilities that, for the price of 1 mill/kWeh, it will assume the burden of spent fuel disposition, it has yet to do so. The combined prospects of continued utility assumption of the storage burden, together with the possibility of private sector assumption of some or all of the cost of disposing of future waste, have acted as crippling handicaps to the industry. The eventual cost of waste disposal as reflected in DOE's own estimates of the YM TSLCC, is hardly a known quantity.



The Cost of Delaying Yucca Mountain

- The TSLCC does not reflect costs associated with the delay of Yucca Mountain's opening date.

- Under the Waste Policy Act, DOE obligated itself to assume the burden of managing spent fuel as of 1998. This will not take place until 2010 at the earliest.

- Estimates of the cost to utilities following from this further 12 year storage burden range from $2 bn (DOE) to $50 bn (Nuclear Energy Institute).

- The industry's perceived $50 bn liability, recast in terms of COE, corresponds to roughly 5 mills/kWh, five times the cost assessed for repository disposal.

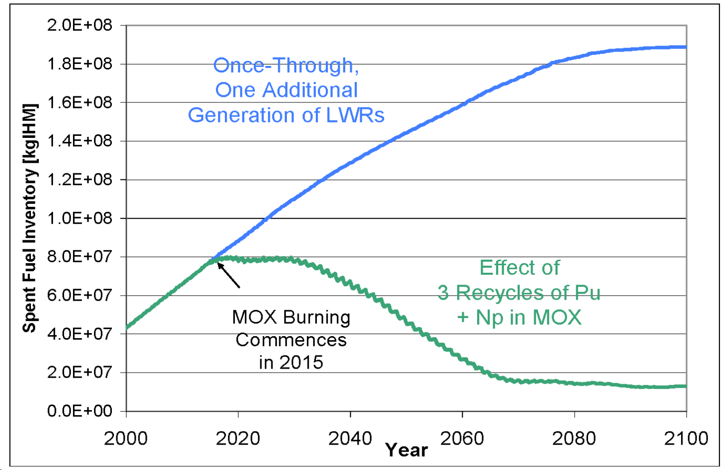
Transmutation Reduces the Burden on Yucca Mountain

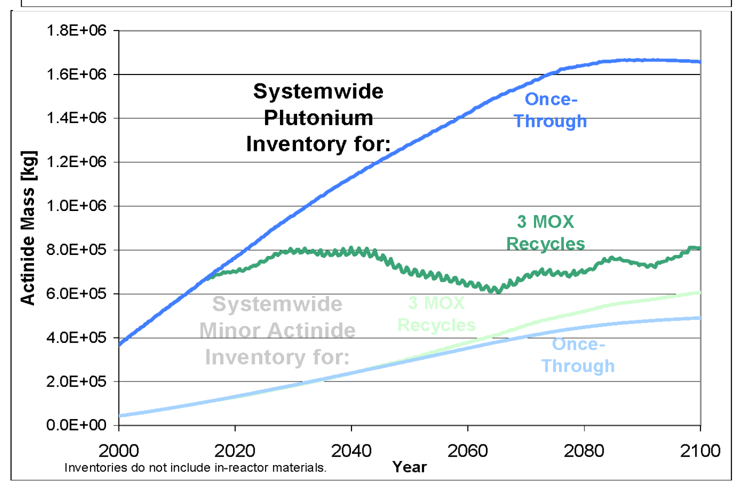
A Solution. Any strategy that calls for direct repository disposal of all spent nuclear fuel will eventually condemn nuclear power to phaseout.

The persistent and growing spent nuclear fuel legacy in the United States constitutes a risk barrier to entry for new capacity. While this risk premium is difficult to quantify, indications are that it, more than construction times and costs, is stifling nuclear growth in the US.

Transmutation offers a solution. It closes the nuclear fuel cycle by recycling actinide materials in reactors until they are fissioned. In doing so, it extracts energy from these elements that otherwise would have gone unutilized. It is the only way – short of waiting millions of years for natural decay to occur – to permanently dispose of these materials.

Recycling Reduces Waste Production





A Disposal Costing Model Based Upon Repository Heat Load Limitations

Unit repository disposal costs for spent fuel, less transportation-related charges, are currently estimated by OMB as ca. $440/kgIHM.

Disposal costs include vitrification – the glassification of high-level radioactive waste (HLW) in an inert matrix – as well as emplacement of this waste in Yucca Mountain.

The capacity of Yucca Mountain is governed not by the mass of material emplaced, but rather by the *total decay heat production* of that material.

Comparing the heat production for high level waste of various compositions to that of spent nuclear fuel, one can estimate an 'effective' repository capacity and thus arrive at a cost estimate.

Disposal Cost as a Function of Waste Content

The ‘equivalent’ heat load-based repository utilization of HLW is the amount [in kg] of the ca. 83000* tonHM Yucca Mountain capacity used by HLW of a given composition originating from 1 kgHM.

This figure, as well as the derived volume of HLW glass, allows the disposal cost is formulated based upon a

- $300,000/m^3 HLW unit vitrification cost (Source: Hanford HLW vitrification program),
- $332 per ‘equivalent’ kg HLW repository disposal cost, representing $440/kg less the YM cost component relating to waste package fabrication.

*Yucca Mountain’s *legislated* capacity is 63,000 tons; however DOE estimates its *actual* capacity at 83,000 tons.

Disposal Cost Comparison

Waste Composition	Unit vitrification cost [$/kg waste]	Unit emplacement/ disposal cost [$/kg waste]	Total [conditioning + disposal] [$/kgIHM]	'Effective' repository capacity [kgIHM]
All Spent Fuel	N/A	440	440	83800
Transuranics (TRU), Fission Products (FP)	3231	6436	498	83800
TRU, Low Heat Release FPs (LHRFP)	922	4087	238	143300
Minor Actinides (MA), LHRFP	757	3484	161	210300
MA, all FP	3686	7052	451	93900
All FP	3323	6274	390	108900
LHRFP	480	897	50	846400

The Advanced Fuel Cycle Initiative: Paths Forward for Nuclear Power

The advanced fuel cycle is in great measure a response to the problem posed by the SNF legacy. Its objectives include:

- **reduction of SNF volume, radiotoxicity and heat load,**
- **recovery of the energy value of SNF,**
- **eliminating the technical need for a second repository,**
- **providing the technical basis for deployment of new nuclear facilities and infrastructure,**

regardless of the path market forces dictate for nuclear power.

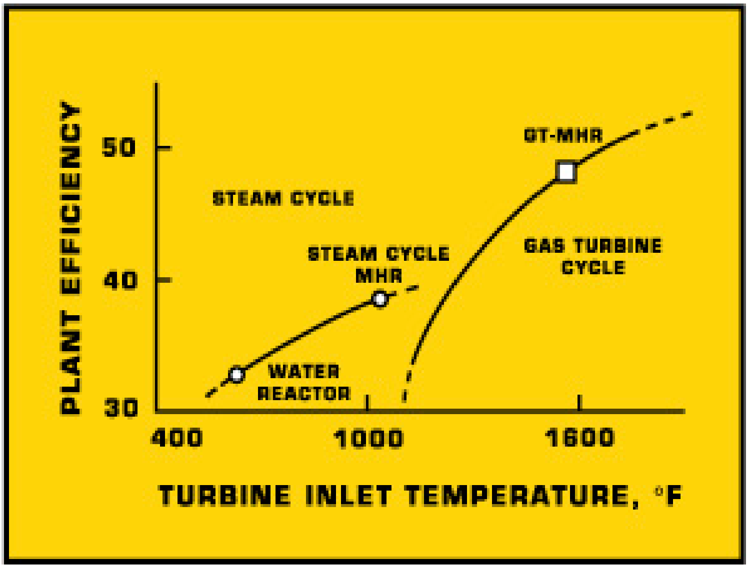
The advanced fuel cycle encompasses a suite of technologies. In addition to advanced versions of present-day LWRs (ALWRs), perhaps recycling plutonium and other transuranic elements in mixed oxide fuel (MOX), we might see high-temperature gas-cooled reactors (GCRs), fast-spectrum reactors (FRs) and accelerator driven systems (ADS).

High-Temperature Gas Cooled Reactors

These reactors use helium or carbon dioxide as a coolant with a graphite moderator. The General Atomics GT-MHR (Gas-turbine modular helium reactor) is an example.

Using inert helium as a coolant with graphite and uranium oxycarbide fuel elements allows for a much higher fuel burnup (double that of LWRs).

Gas-cooled reactors operate at outlet temperatures of up to 900 °C, resulting in a greatly improved thermodynamic efficiency (48% compared to 34% for current reactors).

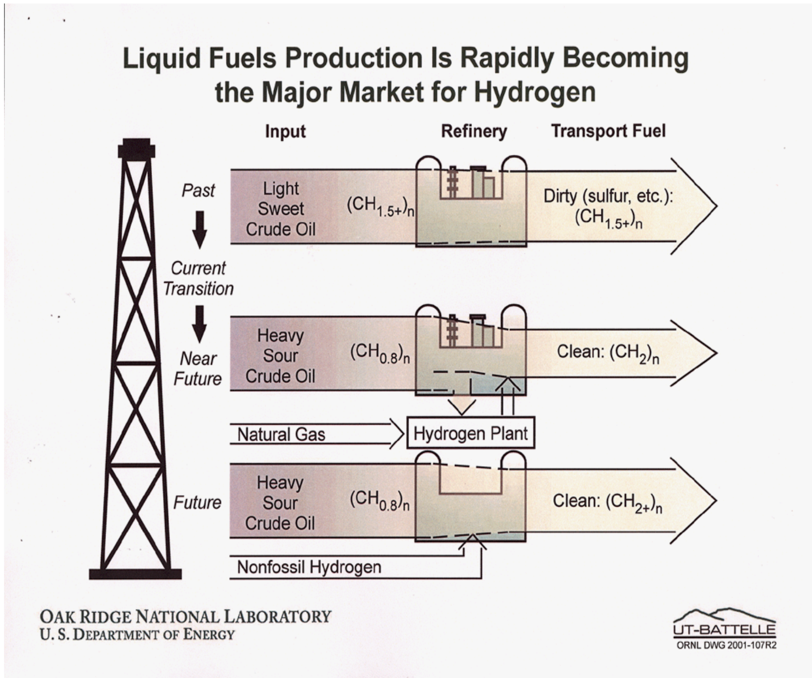


Additionally, the high-temperature process heat of a GCR makes it an ideal candidate for hydrogen production via thermochemical water-splitting. At 900°C, the sulfur-iodine (S-I) catalyzed cycle is more cost-effective than conventional electrolysis.

Existing Hydrogen Economy

- US consumption of hydrogen is 11 Mtonne/yr [50 GWt based on HHV of 141.9 MJ/kg, or 1.56 EJ/yr, ~1.5% US Primary Energy demand(consumption)];
- Most is used in fertilizer, chemical and oil industries;
- 95% produced by Steam Reforming of Methane (SMR):
  - Consumes 5% of our natural gas usage;
  - Releases 61 MtonneCO_2/yr;

- *"Hydrogen Economy" needs ~18X current production for transportation and ~40X for all non-electric.*



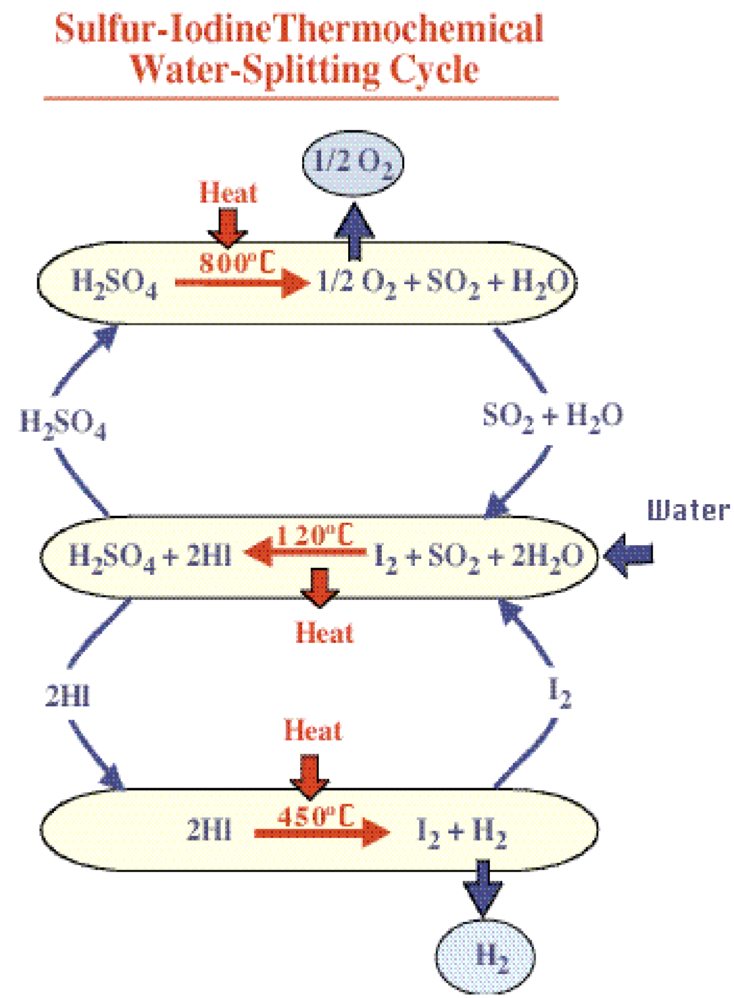
For a more complete discussion of this issue, see [9]

Nuclear Energy Can Provide Hydrogen in Required Amounts

- **A Hydrogen Economy makes sense only if hydrogen is produced without emitting greenhouse gases;**
- **Options for large-scale production are limited;**
- **Nuclear production of hydrogen provides and option:**
  - **Electric power generation for Direct Electrolysis:**
    - **Proven technology;**
    - **Overall efficiencies range from ~27% (LWR with 34% thermal conversion efficiency and 80% electrolyzer efficiencies) to ~41% (HTGR with 51% thermal conversion efficiency and 80% electrolyzer efficiency);**
  - **Heat generation for Thermochemical Water-Splitting:**
    - **Developing technology;**
    - **A set of chemical reactions that use heat to decompose water into H_2 and O_2;**
    - **Net plant efficiencies (heat to hydrogen) as great as ~50%.**

S-I cycle for Nuclear Production of H_2

- Invented at GA in 1970s:
  - Serious investigations for nuclear and solar heat sources;
  - Chemistry reactions all demonstrated;
  - Materials candidates selected and tested;
- Advantages:
  - All fluid continuous process;
  - chemicals all recycled; no effluents;
  - High projected efficiency, ~50%;
- Challenges:
  - Requires high temperature, >800°C;
  - Must be demonstrated as a closed loop; under commercially relevant conditions;
  - Economics must be verified;



Future Hydrogen Economy Based on Supplying 100 % of Transportation Sector

- **Steam reforming of methane (SRM) would use 100% of current natural-gas production;**

- **Present methods (SRM) would produce 1.5 GtonneCO_2/yr (0.41GtonneC/yr; global emissions ~6 GtonneC/yr);**

- **Nuclear production infrastructure needed for H_2 production to supply 100% of transportation sector:**

  - 2,000 GWt could produce 221 MtonneH_2/yr [for high efficiency (50%) nuclear-chemical facility];

  - At least ~7X larger than present US nuclear capacity (consisting of light-water reactors at ~100 GWe or 295 GWt).

Needs and Issues

- Demonstration of the S-I cycle:
  - Technical issues:
    - -- Closed-loop operation and control, reagent cross-over, impurity build-up;
    - -- Materials demonstration (H_2SO_4 and HI decomposition steps at high temperature);
    - -- HI reactive-distillation process system;
  - US/French demonstration planned;
  - S-I Pilot Plant(30 MWt) producing H_2 at a rate of 10tonne/d: ~$50M;
- Reactor design modification and demo facility (MHR):
  - Intermediate loop, circulator and heat exchanger design;
  - Advanced fuel development (to permit higher temp operation);
  - 600 MWt MHR-S-I demo facility (200 tonneH_2/d) : ~$1B;
- Safety and licensability;
- Economics ;
- Infrastructure (for MHR pathway):
  - generation (centralized *versus* distributed or localized);
  - storage;
  - transportation;
  - distribution.

"Top-Level" Cost Esimtates[(a)]

Modular Helium Reactor Capital and Unit Costs for NOK 4X600 MWt Plant[(a)]						
		GT-MHR	PH-MHR	IHT Loop	S-I Plant	Total H2
Account	Direct Costs (2002 M$)	4X286 MWe	4X600 MWt	2400 MWt	2400 MWt	Plant
20	Land and Land Rights	0	0			
21	Structures and Improvements	132	132			
22	Reactor Plant Equipment, RPE	443	343			
23	Turbine Plant Equipement, TPE	91	0			
24	Electric Plant Equipment, EPE	62	50			
25	Miscellaneous Plant Equipment, MPE	28	28			
26	Secondary Heat Transport					
26.1	Heat Rejection or S-I Plant	33	0		534	
26.2	Intermediate HT Loop			73		
90	Total Direct Costs, TDC	789	553	73	534	1160
91	Construction Services and Engineering, CS&E	78.9	55.3	8.76	64.08	
92	Home Office Engineering and Services, HOE&S	78.9	55.3	8.76	64.08	
93	Field Office Enginnering and Services, FOE&S	78.9	55.3	8.76	64.08	
94	Owner's Costs, OC	39.45	27.65	3.65	26.7	
95	Process Contingency, PRCC	0	0	0	0	
96	Project Contingency, PRJC	78.9	55.3	10.95	80.1	
97	Interest During Construction, IDC	188.8	132.3	18.8	137.5	
98	Escalation During Construction, EDC	0.0	0.0	0.0	0.0	
99	Total Cost, TC	1332.8	934.2	132.7	970.5	2037.3
	Unit Total Cost, UTC($/We,t)	1.1651	0.3892	0.0553	0.4044	0.8489
	Cost of Hydrogen, COH($/GJ)	10.75	4.07	0.58	5.44	10.09
	Cost of Hydrogen, COH($/kg)	1.53				1.43
	Cost of Electricity, COE(mill/kWeh)[(b)]	21.91				50.25
	Cost of Electricity, COE(mill/kWeh)[(c)]					43.24

[(a)] Adopted from K. R. Schultz, L. C. Brown, G. E. Besenbruch, and C. J. Hamilton, " Production of Hydrogen by Nuclear Energy: the Enabling Technology for the Hydrogen Economy," General Atomics report (2001).

“Top-Level” Cost Esimtates (cont.-1)

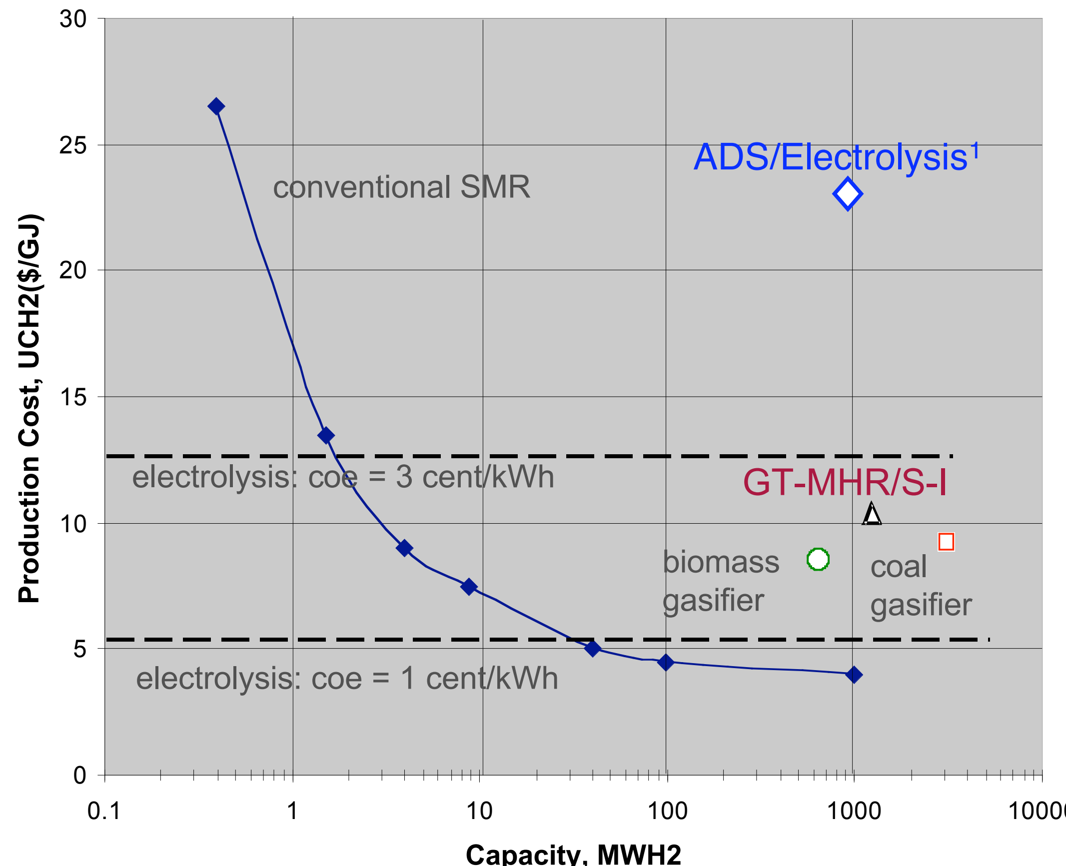
Plant and Financial Parameters					
		MHR	IHT Loop	S-I Plant	
Number of MHR Units	N	4	4	4	
Capacity per MHR Unit, MWt,e	PE,TH/N	286	600	600	
Capacity of N Units	PE,TH	1144	2400	2400	
CS&E as a Fraction of Account 90	fCS&E	0.1	0.12	0.12	
HOE&S as a Fraction of Account 90	fHOE&S	0.1	0.12	0.12	
FOE&S as a Fraction of Account 90	fFOE&S	0.1	0.12	0.12	
OC as a Fraction of Account 90	fOC	0.05	0.05	0.05	
Process Cont. as Fraction of Account 90	fPRCC	0	0	0	
Project Cont. as Fraction of Account 90	fPRJC	0.1	0.1	0.15	
IDC as a Fraction of Accounts 90-96	fIDC	0.165	0.165	0.165	
EDC as a Fraction of Accounts 90-96	fEDC	0	0	0	
Fixed Charge Rate, 1/yr	FCR	0.1	0.1	0.12	
O&M as Fraction of Total Cost	fOM	0.04	0.04	0.06	
Thermal or H2 Conversion Efficienies	etaTH,H	0.4767	1	0.5	
Availability Factor	pf	0.85	0.85	0.85	0.85
Fuel Cell Efficiency	etaFC				0.85
Electrolyzer Efficiency	etaEL				0.80
Specific Energy for H2, EH	EH(MJ/kgH2)				142
Unit Cost of Fuel Cell	UCFC($/We)				0.3
Unit Cost of Electrolyser	UCEL($/WH2)				0.6

Summary: Hydrogen Production Costs

Source Data: [7]

The cost of S-I catalyzed hydrogen production in a GCR has been estimated to be competitive with gasification and electrolysis.

For the ADS, hydrogen produced by electrolysis is expected to offer superior economics as an energy carrier when compared to electricity.



Sources: [7], [8], [9]

[1]Using reference design of [11] with net electrical output of 1220 kWe per plant and assuming 80% electrolysis efficiency.

Fast Neutron Spectrum Reactors

A wide variety of fast neutron spectrum reactors have been proposed, and a few have been put into commercial operation. However, they share one feature that sets them apart from reactors in operation in the US today. In today's reactors, most neutrons are slowed down to 'room-temperature' speed before causing in a nuclear reaction. In a fast reactor, most reactions are caused by neutrons moving thousands of times faster.

For many actinides, an interacting fast neutron is much more likely to induce fission than a slow one. This has two consequences:

- Fast reactors can 'breed', produce more fuel than they consume, since fewer of the 'extra' neutrons from fission are lost to undesirable absorptions;
- Fast reactors can transmute undesirable actinides that generally don't interact in slow-spectrum reactors.

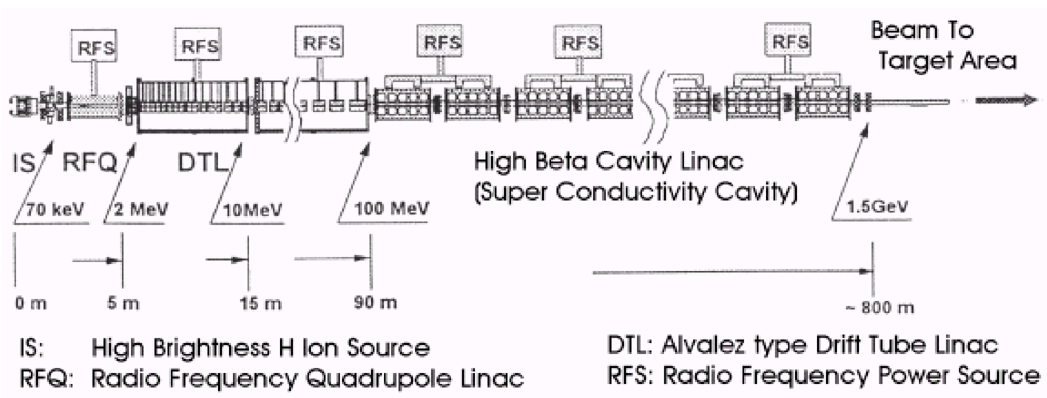
In summation, fast reactors are better than light water reactors at breeding usable new nuclear fuel and destroying unwanted actinide isotopes.

However, they are more expensive to build, and next-generation fast reactor technology is untested. No new FR is expected to be built in the US prior to 2025.

Accelerator Driven Systems

An ADS is a subcritical system: surplus neutrons required to maintain constant power are supplied externally. This is done by means of a proton accelerator and spallation target: each interaction of a very high energy (ca. 1 GeV) proton with the target yields ~ 40 neutrons.

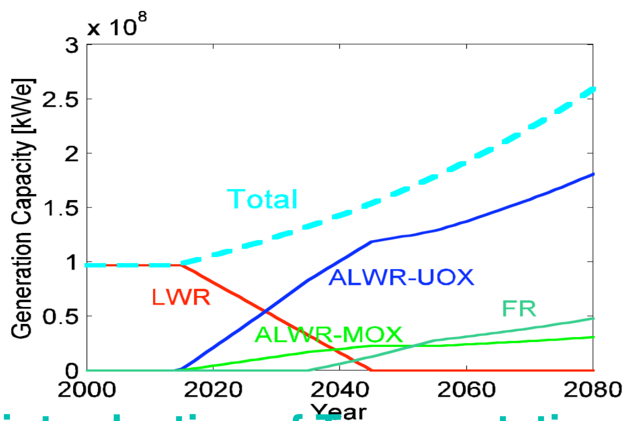
Such a system is not optimized for power production – supplying power to the beam would consume ca. 20% of the electricity produced by the plant. Rather, through the continual injection of surplus fast neutrons, the rate at which actinides are transmuted is optimized.

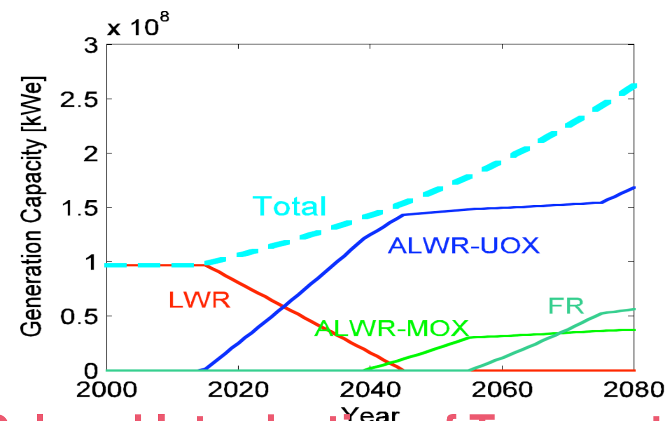


Source: ATSE

The Critical Message: Closing the Fuel Cycle Becomes More Difficult and Costly the Longer it is Postponed

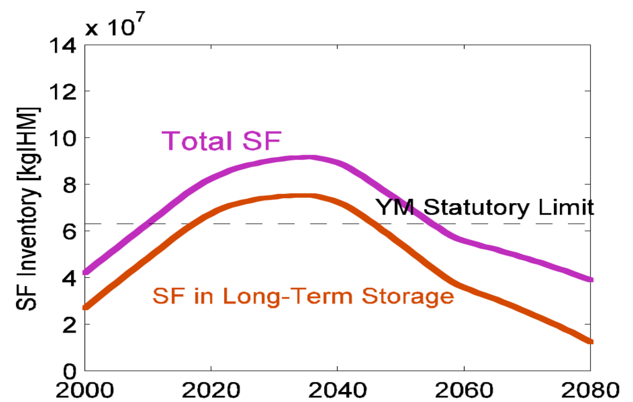
Early introduction of transmutation technologies (left) ensures a sustainable nuclear future even in the case of UOX-driven market share growth. If the decision to transmute is delayed, and the YM II route cannot be taken, a future decision to transmute would result in vast investment and infrastructural impact (notionally indicated by steeper slopes in Tier-1 and 2 generation capacities and in the SF inventory curve).

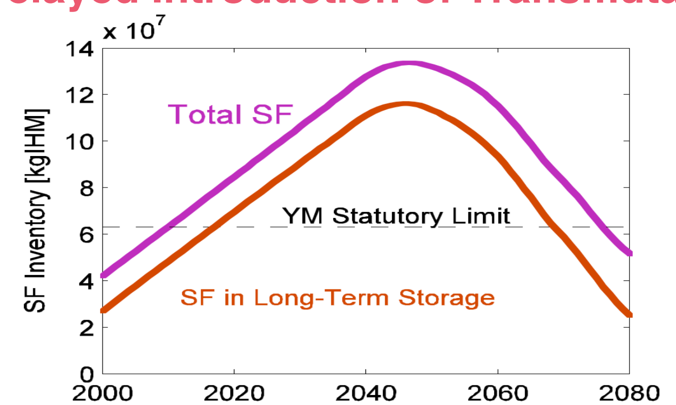




Early introduction of Transmutation

Delayed Introduction of Transmutation



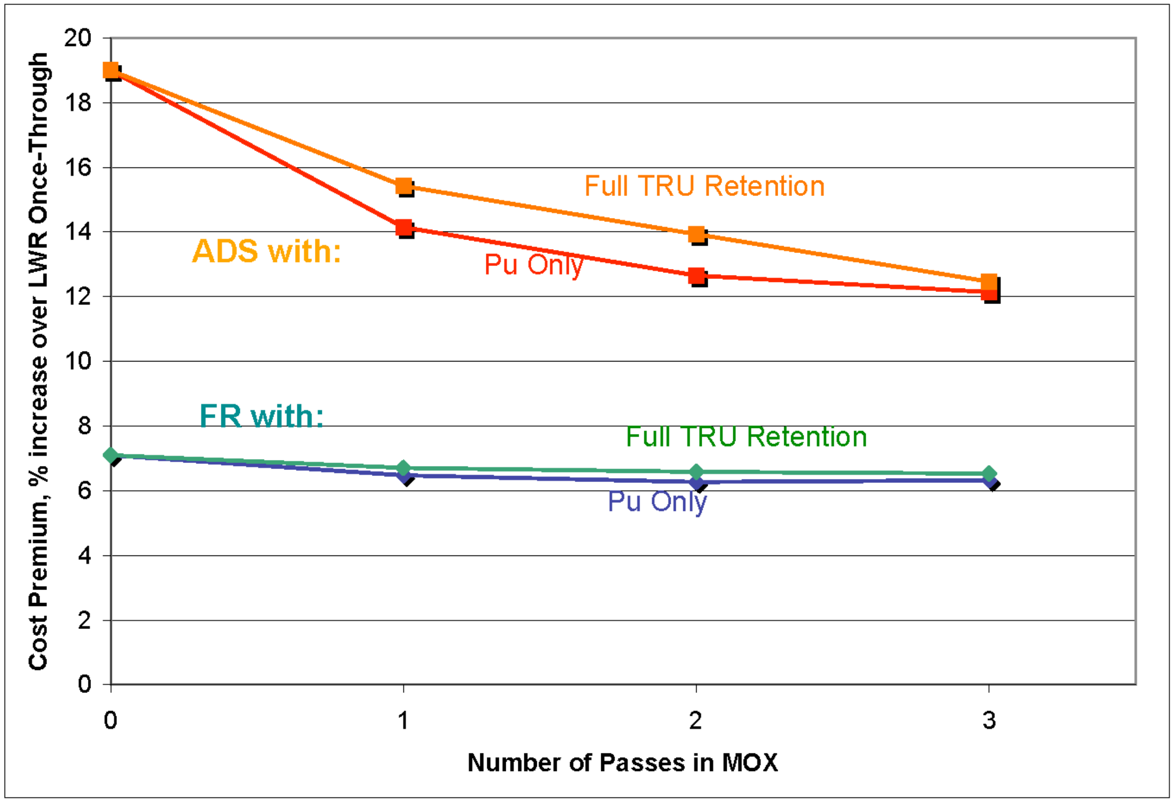


There is a Cost Premium Associated with Transmutation

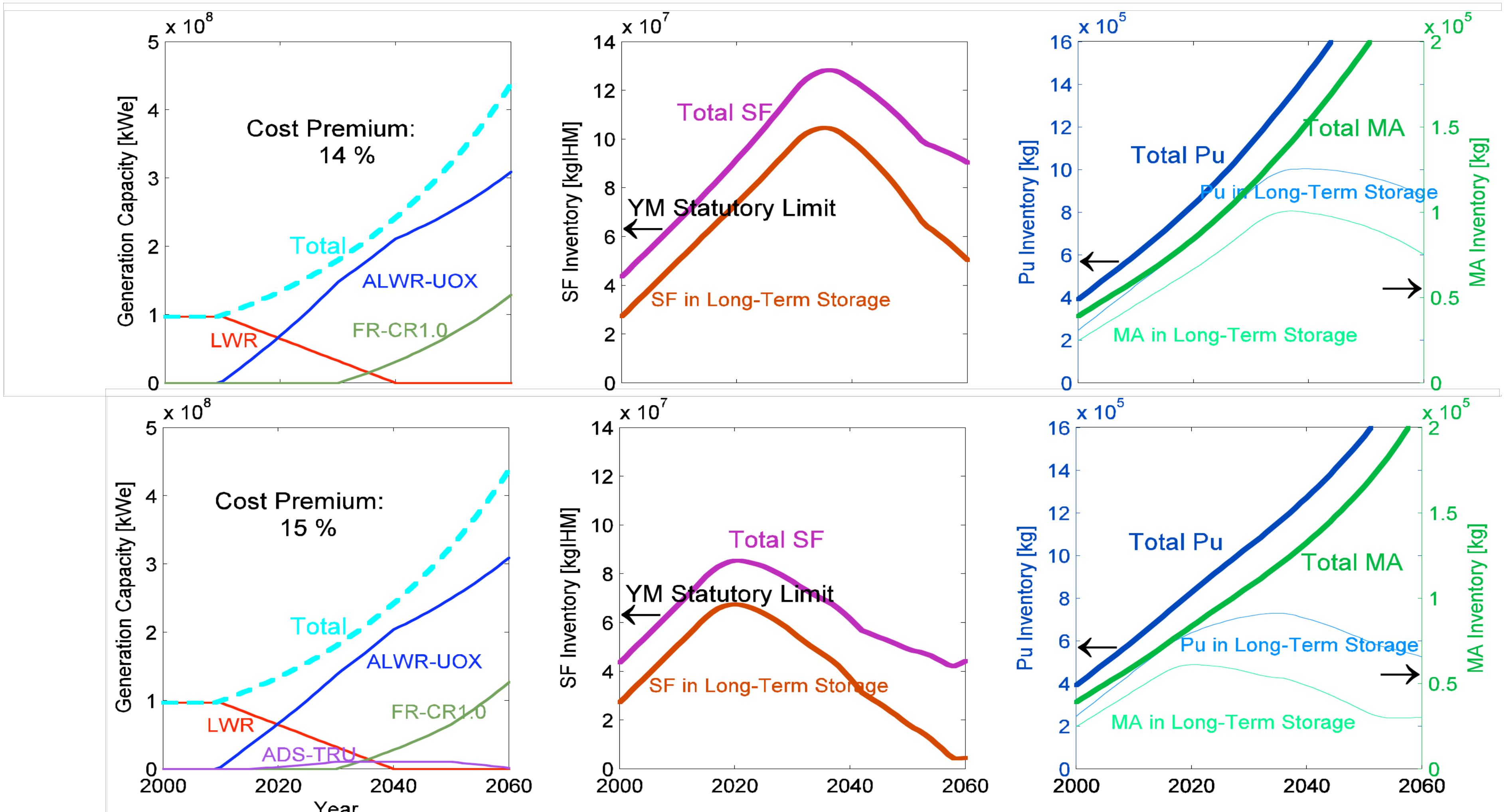
The figure at right shows current estimates of the cost difference between a ‘once through’ strategy and four feasible transmutation-oriented reactor fleets.

These calculations assume an infinite repository capacity with a nominal ($ 500 / kg) cost for repository disposal of spent fuel. **Such assumptions are subjected to parametric evaluation in Ref. [5].**

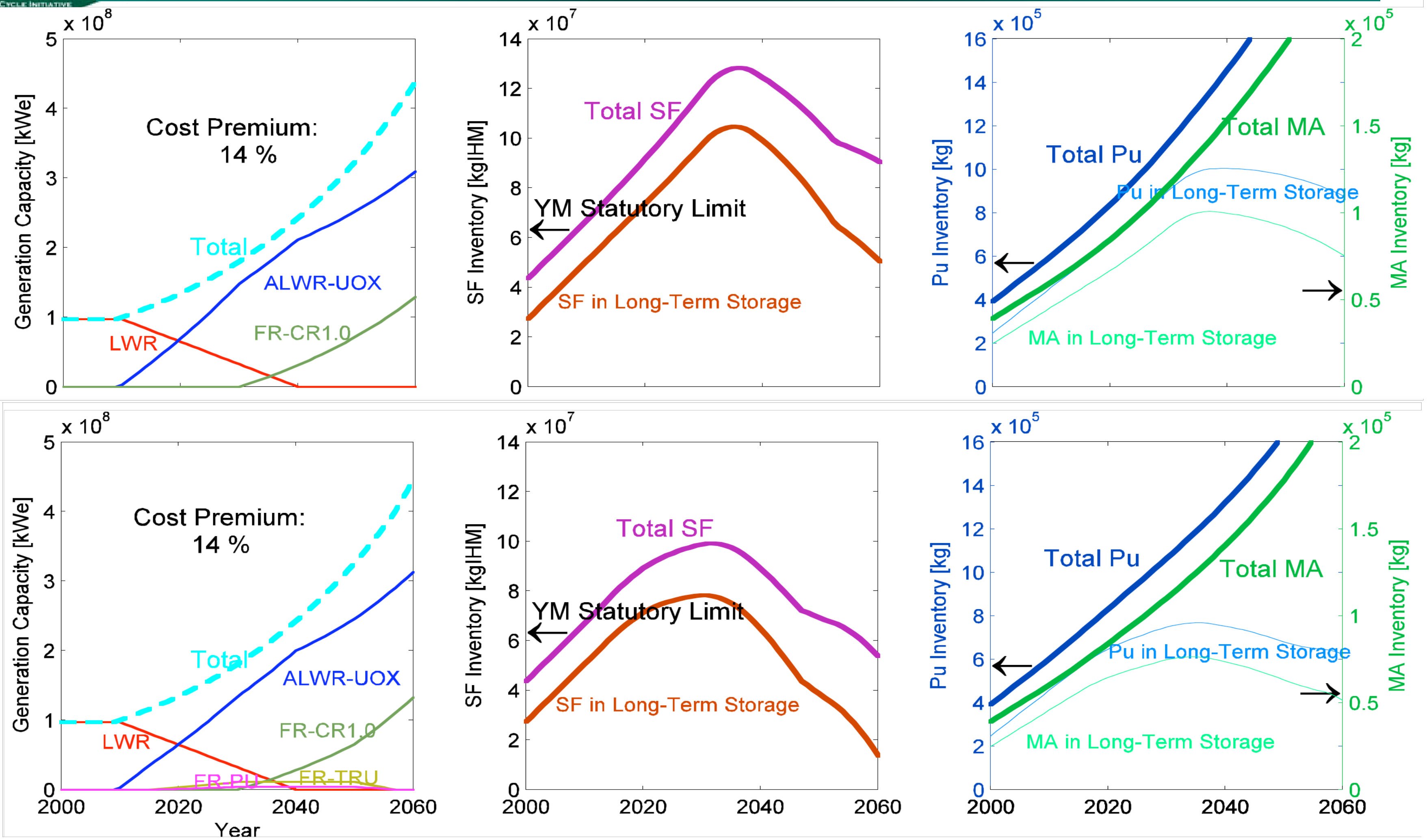
Figure. Cost Premium for Transmutation, Normalized by kWe Delivered to Grid



3% Growth: Transition to a Fast Reactor Economy (top); ADS 'Bridges the Gap' Between ALWRs and Fast Breeder Reactors (bottom)



3% Growth: Fast Burner Reactors Can Also Manage the Stockpile, but Early Deployment is Critical



We Need to Make Decisions on Transmutation in the FY07 to FY10 Time-frame.

- For all growth scenarios, early (2015-20) deployment of a transmutation system greatly reduces the need for long-term engineered storage facilities over the next half-century.

- Is it wise to make investments today on an uncertain fast-growth future for nuclear energy in the next few decades ?
  - Development of non-nuclear energy sources
  - Fusion may become a player in 30-40 years

- If a decision needs to be made in the near future (and it must be if it is going to impact repository decisions), transmutation may be the most attractive technology suite to provide the bridge to a spectrum of nuclear growth scenarios in the future.

Conclusion: The Seven Questions

- The current uranium resource base would support X TW-yr of generation using the once-through cycle. Re-enrichment of depleted U would increase this by 50%. Recovery and re-use of uranium and plutonium in thermal spectrum reactors would provide a further doubling.

A spectrum of options involving fast-spectrum breeders, conservatively assuming a thorium resource base equivalent in size to that of uranium, could ultimately increase this figure to the theoretical maximum of 300*X.

Current estimates of the resource base indicate that X = 100.

The Seven Questions - Continued

2. Technical factors are not the major player in limiting deployed capacity. See question 4.
3. Current generation capacity is 97 GWe in the United States and 360 GWe in the world.
4. Light water reactor technology, by far the most likely candidate for near-term deployment, is well understood. Resource constraints do not play a major role through 2050 at least. The limiting factors are thus not governed by scientific – i.e., requiring major fundamental R&D – constraints, but rather engineering (systemwide cost reductions of ~25% are needed) and social issues. Manufacturers claim the first problem is solved already, and experiences in Europe and Japan bear this out to an extent.
5. Assuming infrastructural additions and retirement of old capacity limit growth rates, capacity additions amounting to 4% per year beginning in 2010 might comprise the most aggressive plausible growth rate. This would result in ~ 1.5 TWe of capacity in 2050. Assuming resource limitations or better economics spur the entry of breeders post-2050, ample plutonium would exist to provide the initial fuel for a breeder fleet (sufficient Pu would exist to commission > 1 TWe of breeder capacity). Growth would then be constrained by the doubling time associated with the breeder technology – for a realistic breeding ratio of 1.2, this would be ~ 20 years.
6. If deployment were to occur on this scale, breeders would probably already be a player and the waste issue would be resolved. The resource constraint would be lifted, and I would expect unit costs to be dropping.
7. There is one misconception – no matter which strategy we pursue, there will always be high-level nuclear waste, in the form of fission products, requiring permanent disposal.

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