

# Dynamic Systems Studies of the the of the Nuclear Fuel Cycle

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22.251 Systems Analysis of Nuclear Fuel Cycle  
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# Fuel Cycle Basics

- The most economic nuclear fuel cycle is the once-through use of mined uranium, as long as uranium supplies remain inexpensive. If nuclear deployment does not increase substantially, once-through will remain the preferred option. However, if nuclear growth is large, then at some future date, fuel breeding in reactors will become attractive, justifying fuel partitioning and recycling of useful parts.
- The benefit to repository capacity depends on thermal load impact and radioactivity containment needs on the design of the repository. For the same nuclear energy output, advanced fuel cycles with recycling produce the same amount of fission products (i.e. heat load for 300 years) but can dramatically reduce the transuranic loading (i.e. long term heat load) of a repository.
- The transition from the once-through cycle to a closed cycle has a slow dynamic, and a complex interdependence of many factors. Thus, a study of fuel cycle dynamics is needed to understand the influence of these multi-coupled factors in growth scenarios of nuclear power.

# Fuel Cycle In Perspective

1. The fuel cycle optimization is a transitory issue. In the short term and in the long term, the choices are well identified. But what to do in the interim?

2008: Once Through: Current LWR Technology

One Tier Recycle: Pu recycle in LWR/ MA to Waste

2100: Recycle of U, Pu and MA in fast breeders

2. There are many options for storage time, separation streams, recycling in reactors and repository designs  
Optimization should be system wide not a single step in the the system (e.g. fuel cycle cost vs electricity cost)

# Fuel Cycle In Perspective

3. Global as well as national implications and constraints: assured fuel resources, industrial infrastructure, waste management and proliferation concerns.

There should be a global collaboration to find the best solutions

4. The time constants of technology choices are relatively short (decades) but those of implications of choices are long (centuries or millennia)

- Economics rules short term effects
- Environment rules long term effects
- National security (including energy security) affects both

# Dynamic simulation of the fuel cycle

- MIT has developed a code, CAFCA, that tracks the demand for various facilities and fuel resources associated with a given scenario for demand for nuclear energy in the future.
- The code uses the “system dynamics” code VENSIM as a bed for simulation of the relations and material flows between various technology options. CAFCA has several models for economic analysis.
- In 2008- 2009, the code was benchmarked for four different simplified advanced fuel cycle scenarios against simulation codes from three other organizations:
  - VISION: INL-team developed it for the DOE- AFCI program
  - COSI: CEA developed code with much more detailed for the reactor physics characteristics of the chosen technology
  - DANESS: THE ANL developed codes that was spun off as a commercial code outside the US.
  - In principles DANESS and VISION can track individual batches, but that is not done in CAFCA or COSI. Therefore, this feature was not addressed in the benchmark study.

# MIT Study of the Nuclear Fuel Cycle

## Dynamic simulation of the fuel cycle

- Scope and objectives of the study:

Examine implications of a reasonable range of nuclear energy growth rates on various nuclear fuel cycle options over this century. Derive recommendations for implementation over the next decade with respect of policy and R & D portfolio.

- Key Questions:

- ★ How would various fuel cycle options impact demand for nuclear fuel resources, mined or recycled?
- ★ What are the amounts of stored spent fuel, transuranics (TRU) in the system, and waste for a geologic repository implied by the choice of the fuel cycle?
- ★ What is the impact of timing of introducing recycling on the amounts of stored spent fuel, TRU and wastes to be sent to repositories?

# Fuel Cycle Options

*Base cases in red italics*

Once Through:

*Build ALWR/ Current Burnup (50 MWD/kg)*

Build ALWR/ High Burnup (80 MWD/kg)

Thermal Reactor Recycle:

*One Pu recycle of MOX in LWRs*

TRU recycle in LWR via Advanced Fuels

Fast Reactor Recycle:

*TRU to self-sustaining FR (Conversion Ratio =1)*

*TRU recycle in fast burner ABR (with low CR <1)*

*TRU recycle in fast breeder FBR ( with CR>1)*

Other cycles option will be considered in the future

# Choices: Reactors and Recycling

## Light Water Reactor (LWR)

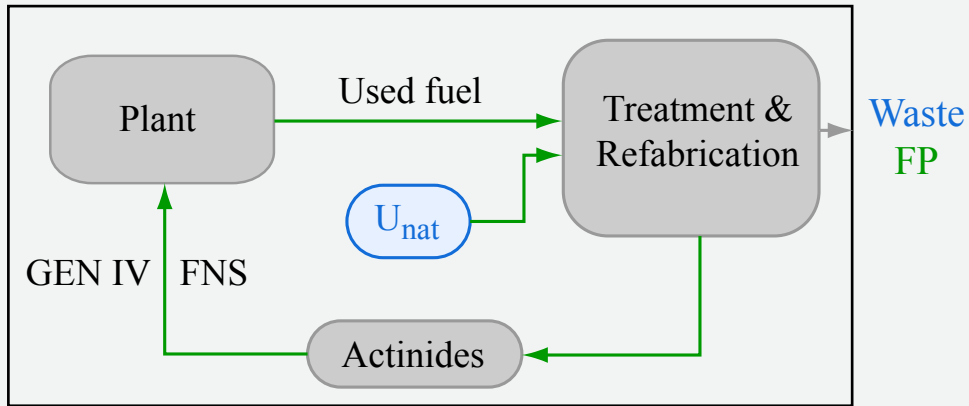
- A core contains 90 MT of heavy metal, requires 20 MT/yr of 4.5% enriched U
- Spent fuel (SNF) contains about 1% TRU, of which 90% is Pu and 10% MA,
- Thus about 0.2 MT of TRU in spent fuel is discharged per year
- MOX is limited to one third of current LWR core. Full core MOX is possible in advanced reactors.
- *11 years of operation of 1 LWR is needed to provide one batch of fresh MOX*
- *Large commercial reprocessing plant 800MT/yr: nearly 0.9 years of operation per one initial MOX core*
- MOX SNF can be reprocessed for recycling of Pu or TRU in LWRs. Multirecycling in LWRs is more challenging than recycle in fast reactors due to buildup of spontaneous neutron sources and non-fissile Pu and MAs

## Fast Reactor Recycle

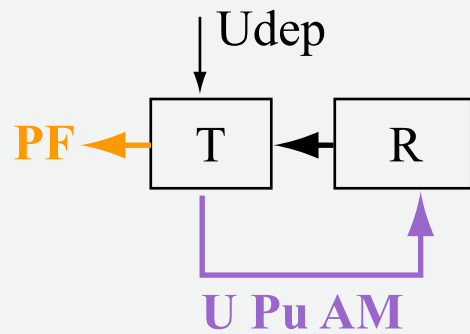
- 1GWe FR initial core requires 7 to 10 MT TRU plus about 50 MT U
- *Thus ~700 to 1000 MT of LWR SNF need to be reprocessed to start one 1GWe FR*
- *35 -50 years of operation of 1 LWR to start 1 FR*
- *Large commercial reprocessing plant 800MT/yr: nearly 0.9-1.25 years of operation per one initial FR core*
- Alternative startup on enriched uranium (at >15% enrichment) is possible, but will reduce U reduction rate.
- 65 MT (full FR core) of FR SNF (15% TRU) yields 65 MT of FR fresh fuel for self sustaining reactors. More for breeders (since  $CR > 1$ ).



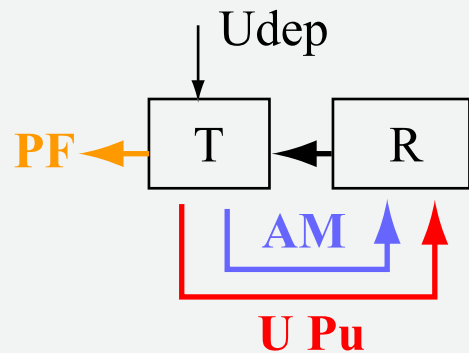
# Flexible Fuel Cycle (U, Pu, MA) + Burning / Breeding



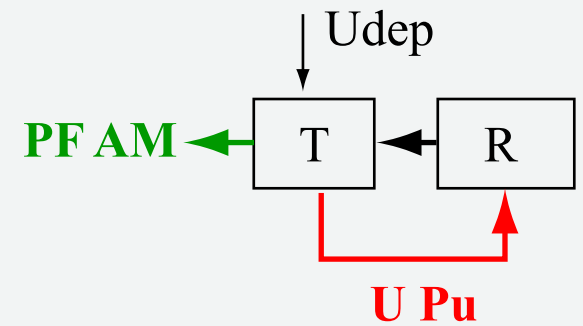
- Resource saving
- Waste minimization
- Non-proliferation



Homogeneous recycling (GenIV)



Heterogeneous recycling



Recycling U Pu only

Image by MIT OpenCourseWare.

# Fuel Cycle Key Assumptions

- Nuclear power will grow after 2020 at rates that vary between 1% and 4%. Maximum allowed installed capacity is 1000 MWe.
- Dates for introduction of and lifetime of various options:
  - Recycling of LWR spent fuel (MOX) **2025**, 2040
  - Reprocessing LWR spent fuel starts **5 years** (10 years) ahead of FRs
  - Fast reactors and their fuel recycling **2040**, 2060
  - FR Recycling plants are built to match reactor build schedule
  - Reactor life time is 60 years. Recycling plant lifetime is 40 years
- Infrastructure constraints applied to recycling technology:
  - Minimum SNF cooling time of **5 yrs** (10 years), **1yr** of recycling, and **1 yr** of fuel manufacturing.
  - Minimum capacity factor of 80% during recycling plant lifetime.
  - LWR fuel recycling plant size: 1000MT/yr, built in 4 years prior to 2050, 2 years after 2050.
  - FR recycling plant size (metallic fuel) 100MT/yr; built in 2 years prior to 2050 then in 1 year
  - **U is recycled for all options.**

# U.S Nuclear Growth Scenarios

## A: 2008 to 2020

- In this period, industrial capacity and regulatory licensing limit the number of new reactors added to grid.
- Nuclear installed power increases to **115 GWe**:
  - **Licensing renewals** (~15 GWe shutdown avoided)
  - **Power uprates** (3 GWe, all applications at NRC)
  - **New plants** - (12 GWe, half of COL applications at NRC).  
EPACT05 provides stronger incentives for the earliest 6 GWe, but those could be shared among many units. At end of August 2008, Construction and Operation License (COL) applications submitted to NRC totaled 23.6 GWe (19 units on 11 sites). Early site applications indicate 31 units are being planned.
- **Capacity factor remains at 90%**. (Note 2007 capacity factor alone was 91.8%).
- This scenario implies 15% increase in nuclear energy consumption in this period, or 1.2% per year, appreciably lower than growth rate of 1.6% from 1998 to 2007

# US Nuclear Growth Scenarios

## B: 2020-2100

- ✓ From 2020 on, three growth rates will be simulated: 1.0%, 2.5% and 4% per year, all new reactors
- ✓ Capacity factor remains at 90% for the entire period
- ✓ This means about 150 GWe, 240 GWe, and 370 GWe by 2050
- ✓ Annual growth of US total electricity consumption (TEC) in the last 10 years has been 1.5%. If this continues, nuclear contribution could be 16%, 26%, or 40%. At 1% TEC growth, nuclear will be 20%, 32%, and 50% in 2050
- ✓ In 2003, the Low/High nuclear cases had 2.5/3.6% growth rate until 2050. Growth rate of TEC in the US was estimated as 1.7%
- ✓ **Constraint** – maximum allowable nuclear share of TEC is 70%. By 2100, this is encountered only for high growth rate scenarios.

# World Nuclear Energy Scenarios

- o For simplicity, World nuclear energy use will be assumed to **remain at 3.5 times that of the US**, as roughly today, for various scenarios.
- o While in the past Europe and Japan were the main other nuclear energy growth countries, in the future it is China, India, and Korea that would be the main growth consumers.
- o In 2003, a detailed model of the world in five categories of countries resulted in a higher TEC and slightly higher nuclear growth rate in the World than the US. Total electricity consumption was assumed to grow at 2.1% per year (vs 1.7% for US). Nuclear low and high consumption growth rates were taken as 2.7% (vs 2.5%) and 3.8% (vs 3.6%) .

# Installed Capacity in GWe

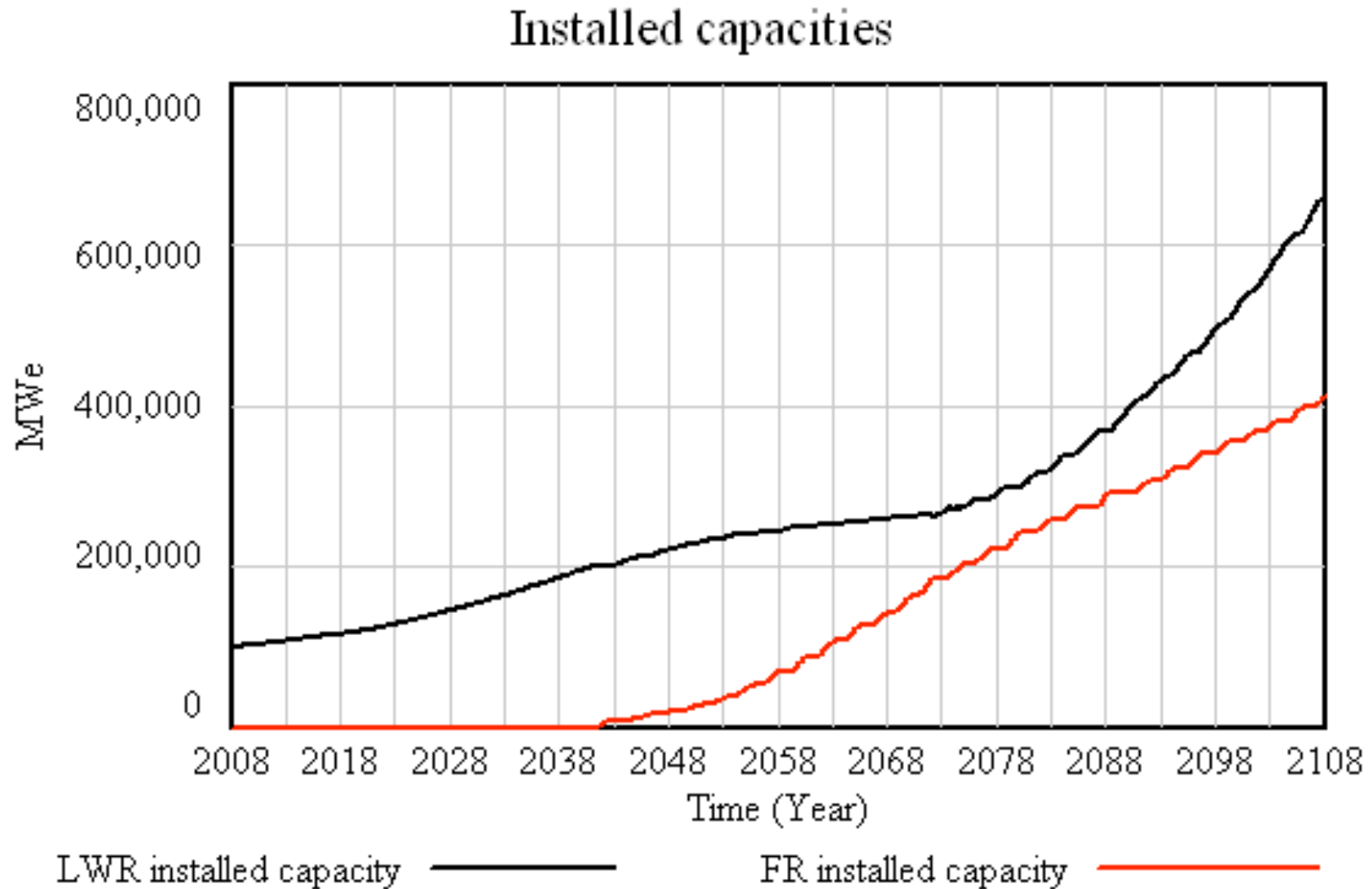
LWRs will play a major role throughout century

Fast reactor conversion ratio beyond 1.0 may not be helpful

Growth Rate	Fuel Cycle	By 2050	By 2100
1.0%	OTC	167	268
	MOX	33	31
	FR*	11; 13; 11	147; 217; 221
2.5%	OTC	250	859
	MOX	40	89
	FR*	21; 23; 20	271; 357; 386
4.0%	OTC	376	1,001**
	MOX	40	123
	FR*	20; 23; 21	368; 485; 498

\* Results are for conversion ratios = 0.75; 1.0; 1.23    \*\* Cap Reached in 2088

# Share of Fast Reactors in case of 2.5%: Can reach near 45% in 40 years



# Cumulative Demand for Uranium (1000 MT)

MOX has little effect, and fast reactors take decades to cause a real difference

Growth Rate	Fuel Cycle	By 2050	By 2100
1.0%	OTC	1,105	3,064
	MOX	961	2,516
	FR*	1,058	1,970
2.5%	OTC	1,382	6,299
	MOX	1,226	5,361
	FR*	1,311	4,060
4.0%	OTC	1,749	8,591
	MOX	1,593	7,295
	FR*	1,679	5,831

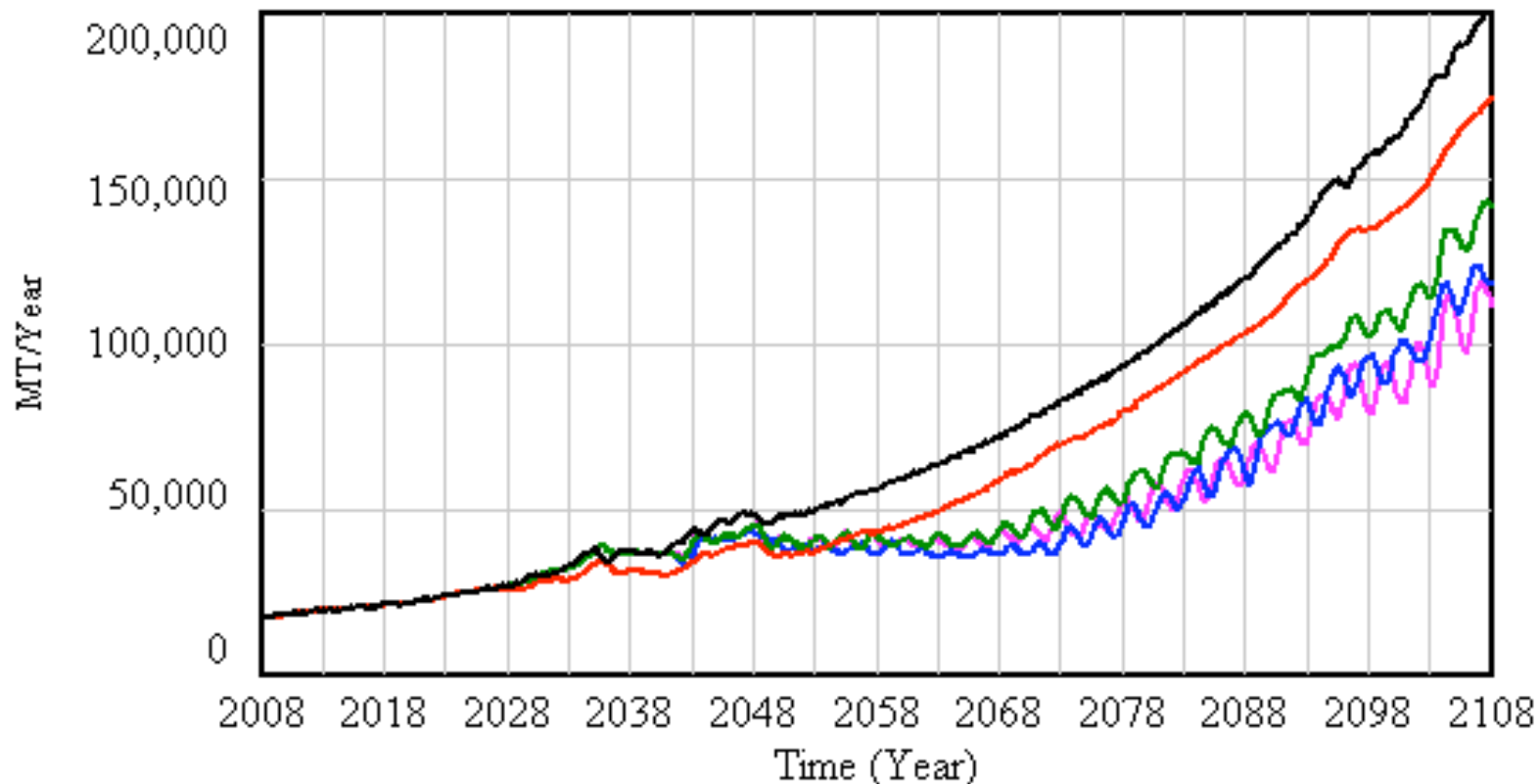
\* For Conversion ratio =1.0



# Natural Uranium utilization rate for 2.5% case

MOX has little effect, little difference between conversion ratios

Natural U utilization rate



Scenario 1 - OTC  
Scenario 2 - MOX  
Scenario 3 - FR CR=0.75

Scenario 4 - FR CR=1.0  
Scenario 5 - FR CR=1.23

# Nuclear Fuel Cycle - Resources

- Uranium-235 is the only naturally occurring isotope that can be used as fuel (fissioned) in nuclear reactors. U-235 is naturally present at 0.71% in U. Uranium is mostly U-238 (99.29%)
- 1 GWe-year requires about 200 MT of natural uranium
- World use in 2007 was about 0.07 million tons of U ore to supply 6% of the world energy (15% of electricity).
- IAEA estimates 5.5 million tons of U in assured sources at costs below \$130/kg. Another 10.5 million tons considered likely.
  - Current U spot price is about \$100/kg, in 2004 only \$40/kg. Peak reached for a short while in late 2007 was \$200/kg
  - At today's prices U cost is only 4-5 % of the cost of nuclear electricity.
  - Large deposits in Australia, Kazakhstan, Canada, Russia, USA and S Africa.
- Experts estimate 25-50 million ton conventional U at reasonable prices.
  - Lower grade uranium from unconventional sources, e.g. sandstone and phosphate may add another 50 MT or more.
  - Sea water has another 5,000 MT, but at low concentration of 3ppm.

# Redbook Resources: Historical Perspective

The known conventional resource base (RAR+EAR-I) has increased in size somewhat over the four decades of OECD recordkeeping, from 3 MT to 5 MT, even as 2 MT of U have been extracted.

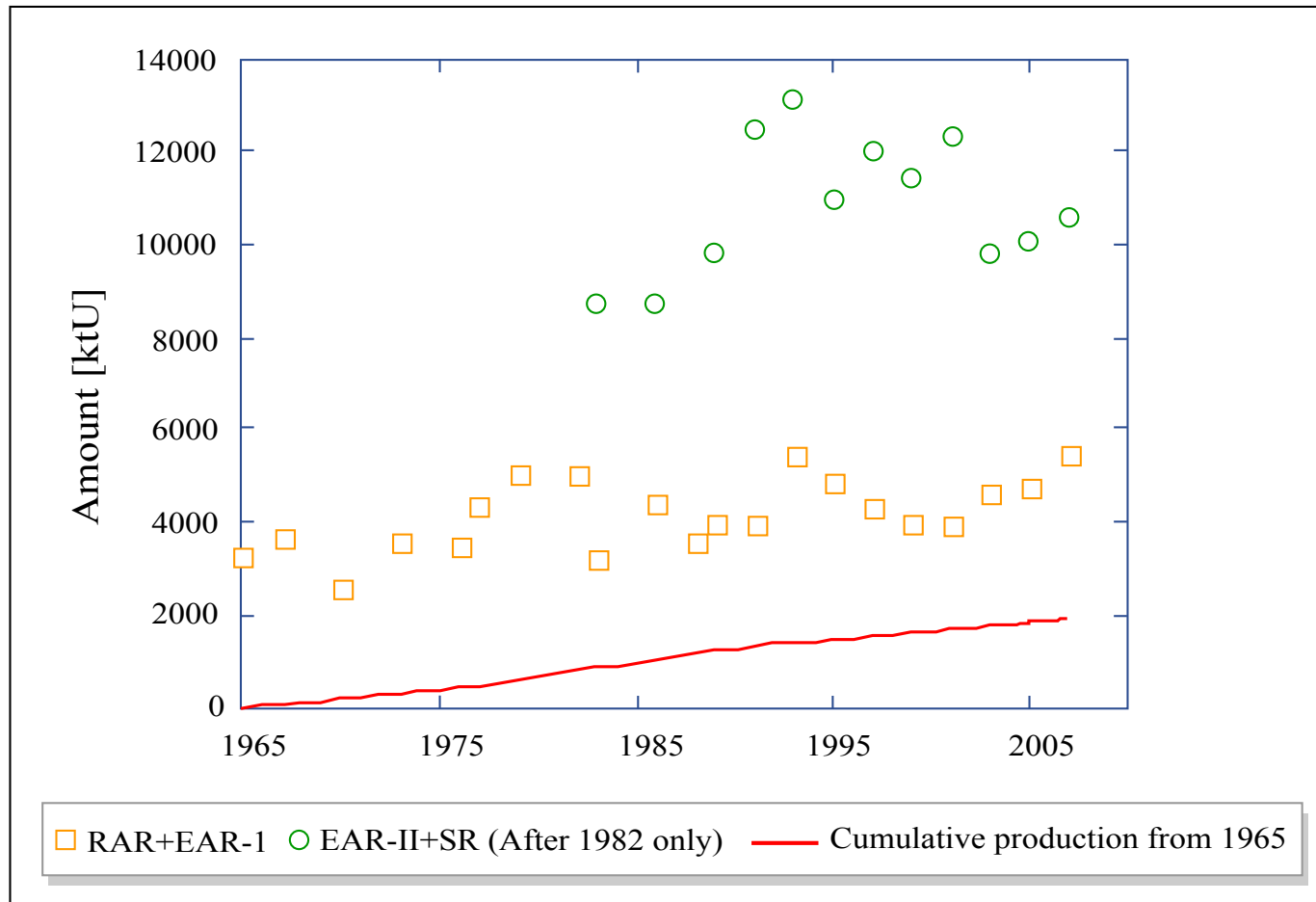


Image by MIT OpenCourseWare.

# Uranium Consumption and Spot Prices

Uranium spot market is about 15% of total. Long term contracts govern the rest

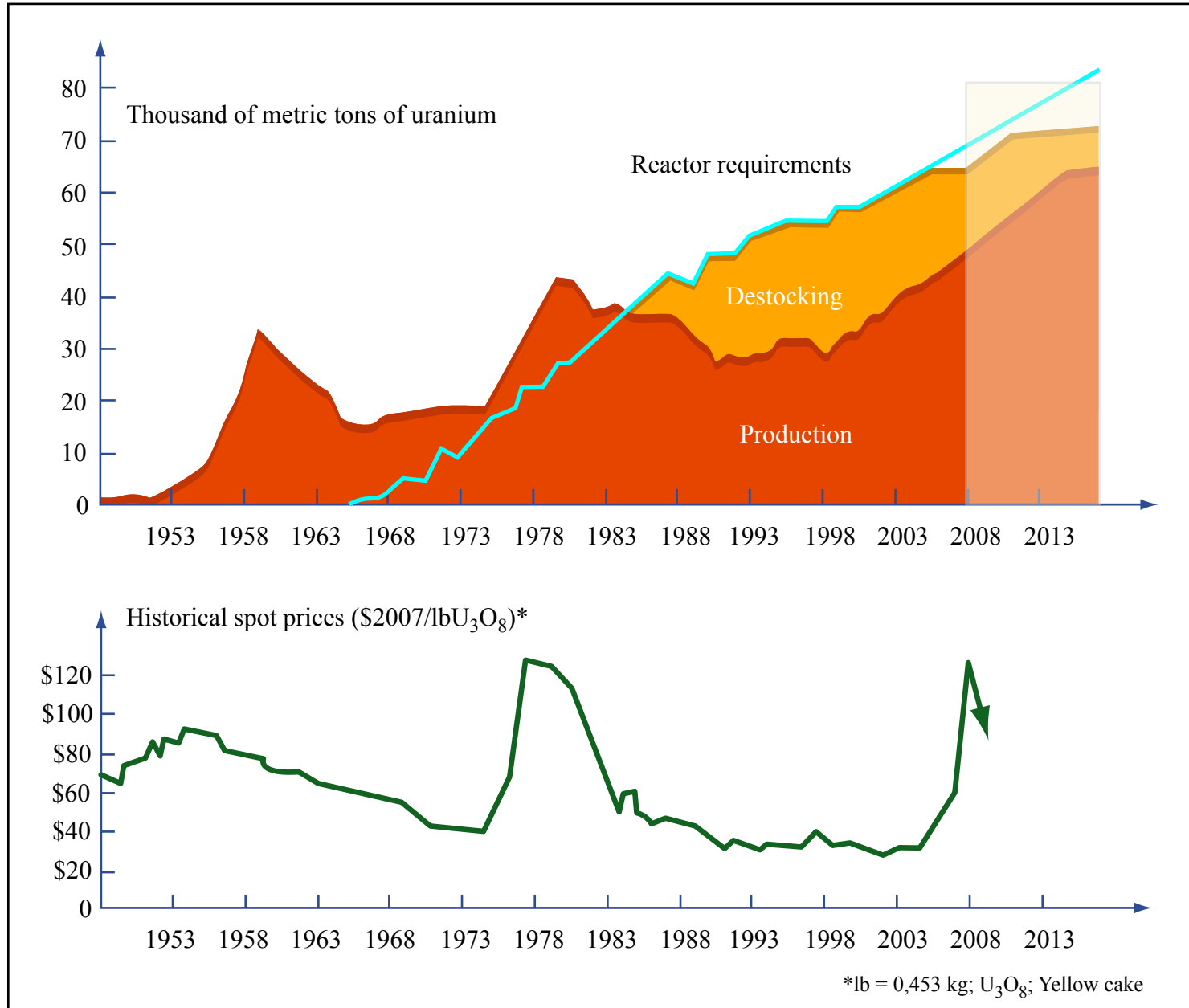


Image by MIT OpenCourseWare.

Source: CEA News, August 2008

# Uranium is a small fraction of Production Cost of Nuclear Electricity

The nuclear electricity production cost is insensitive to the price of its resource. As a rule of thumb, for the once through LWR fuel cycle [a \\$50/kgU rise in the uranium cost yields a 1 mill/kWh increase in generation costs](#) assuming 50 MWd/kgU burnup, DOE, 2009, Advanced Fuel Cycle Economic Analysis.

MIT model predicts 100 years at 5 times today's rate are likely within \$130/kg, or 100 years of 10 times today at \$170/kg

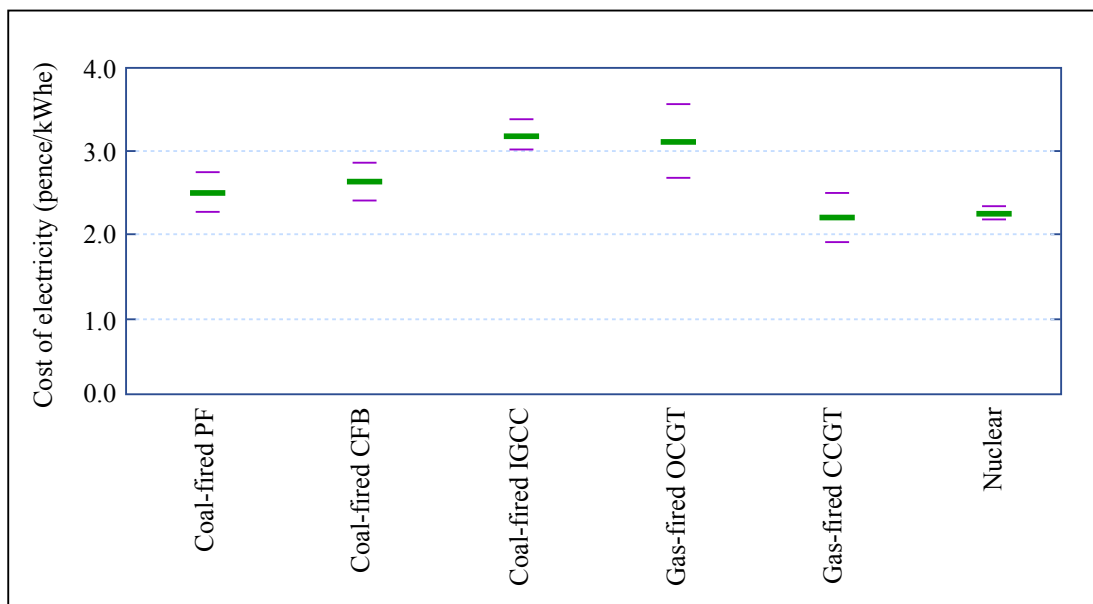


Image by MIT OpenCourseWare.

The figure shows the sensitivity of the cost of generated electricity to a +/- 20% change in fuel price for coal, gas and nuclear. Roughly:

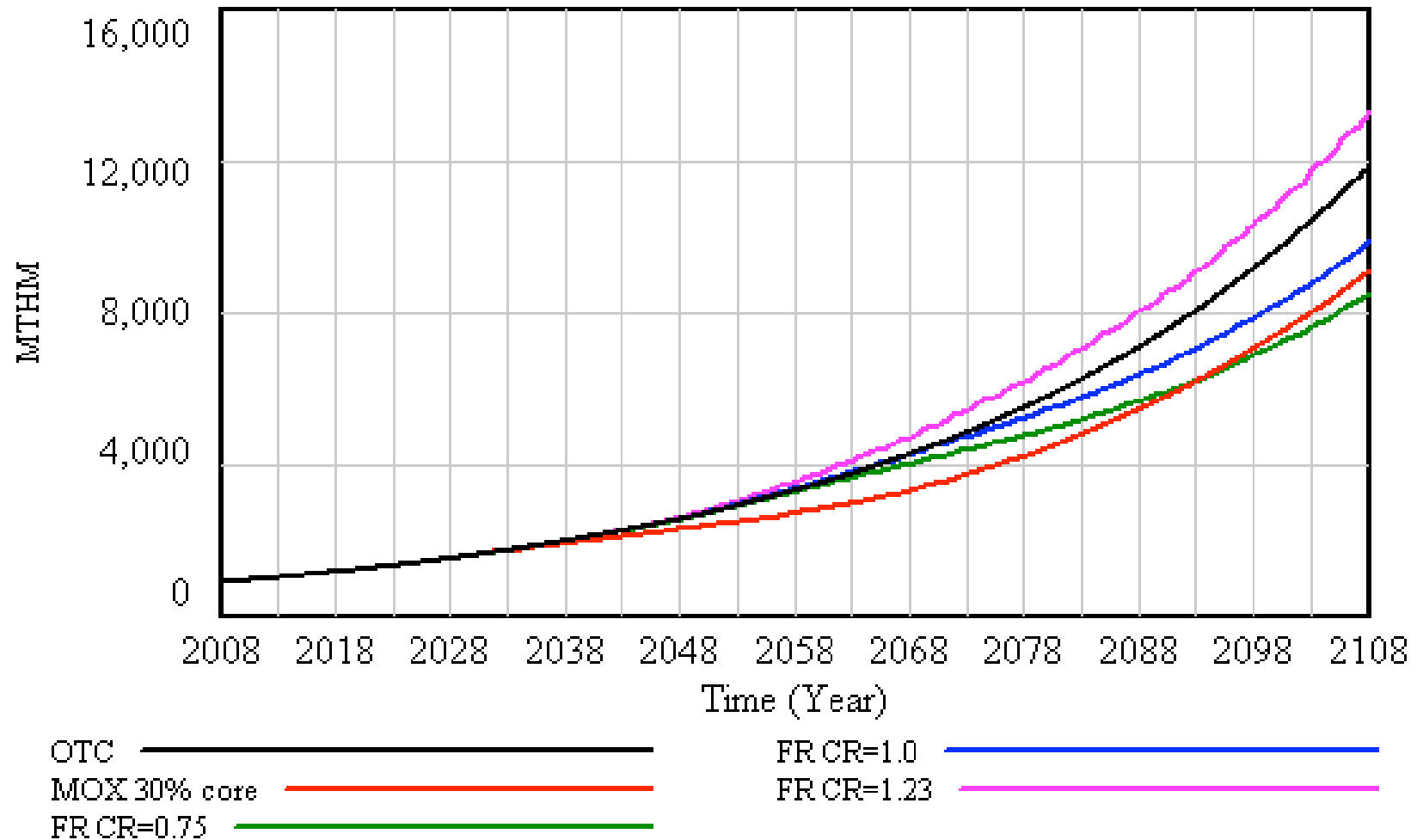
- 1% of nuclear cost
- 6% of coal cost
- 15% of gas cost

Figure Source: Royal Academy of Engineering (UK), "Cost of Generating Electricity," 2004.

# Total TRU in system for 2.5% case

Recycling has a modest effect on total TRU in the system over the first 35 years after introduction

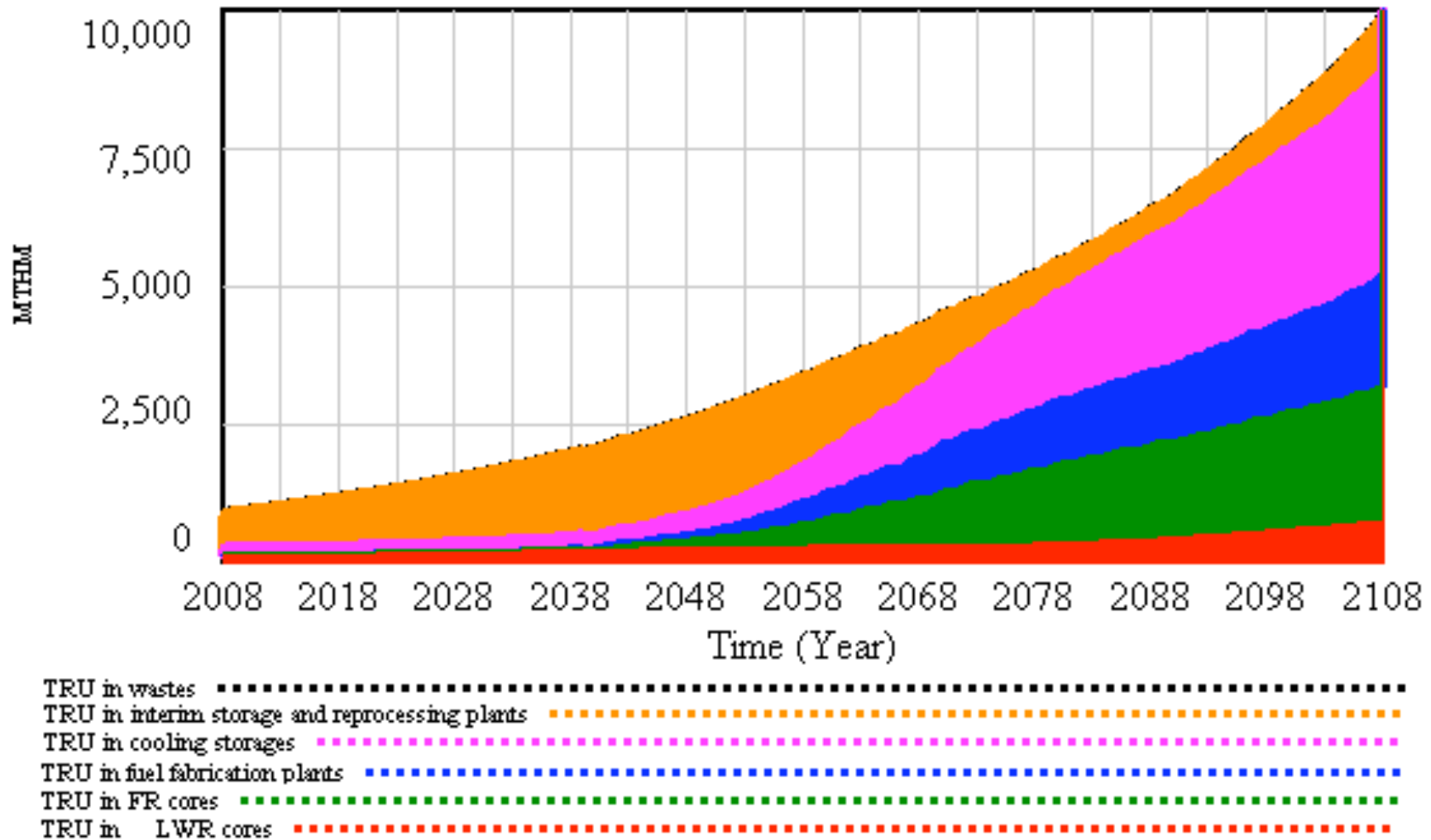
TRU: total mass in the system (plants + storages + repositories)



# Total TRU in system for 2.5% case

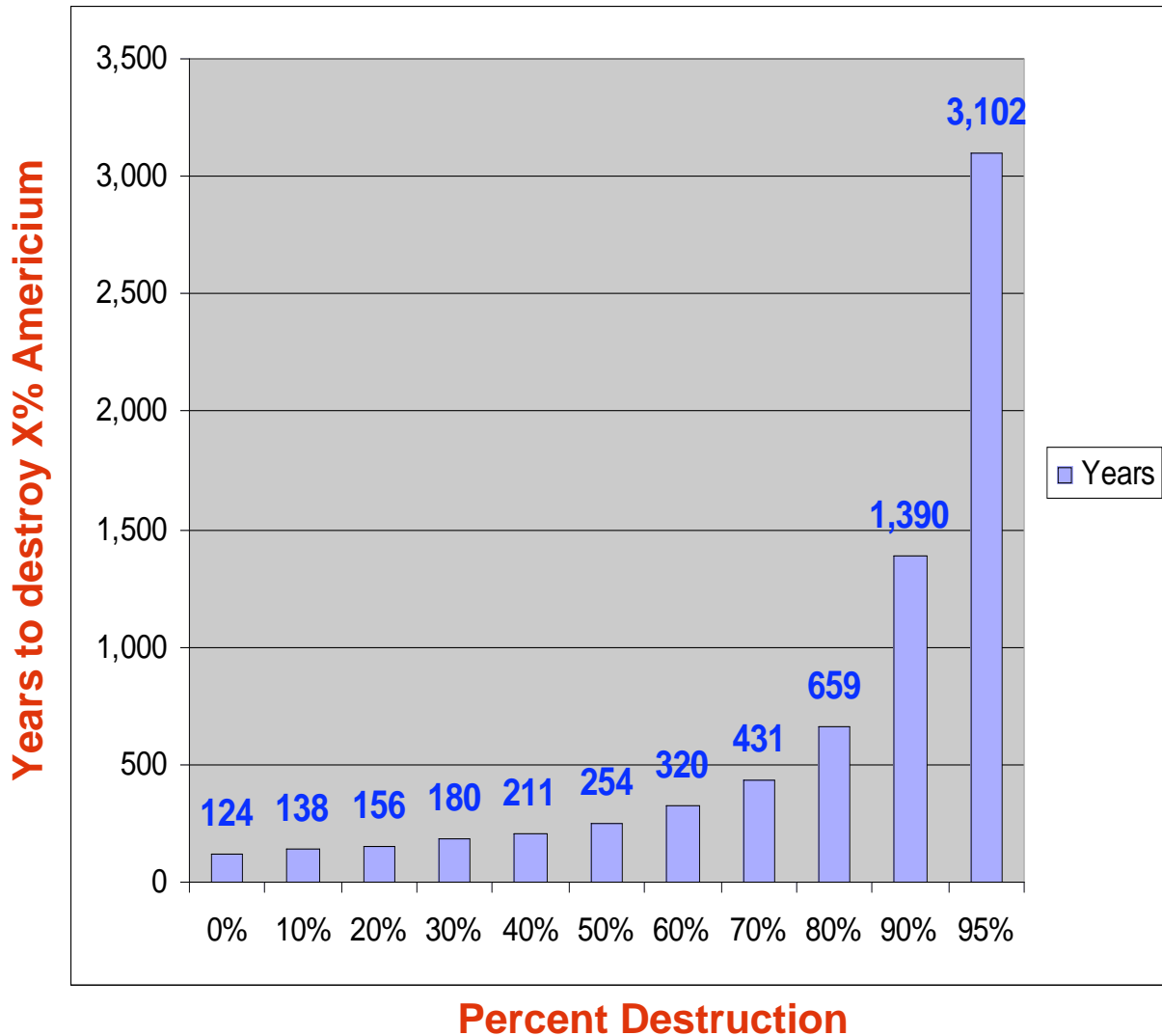
But the TRU is distributed over more secure locations

Total amount of TRU in the system (FR CR=1.0)



# Example of Waste Burn Challenge

## Years to Achieve “Americium (Am)” Reduction Percentage (EPRI)

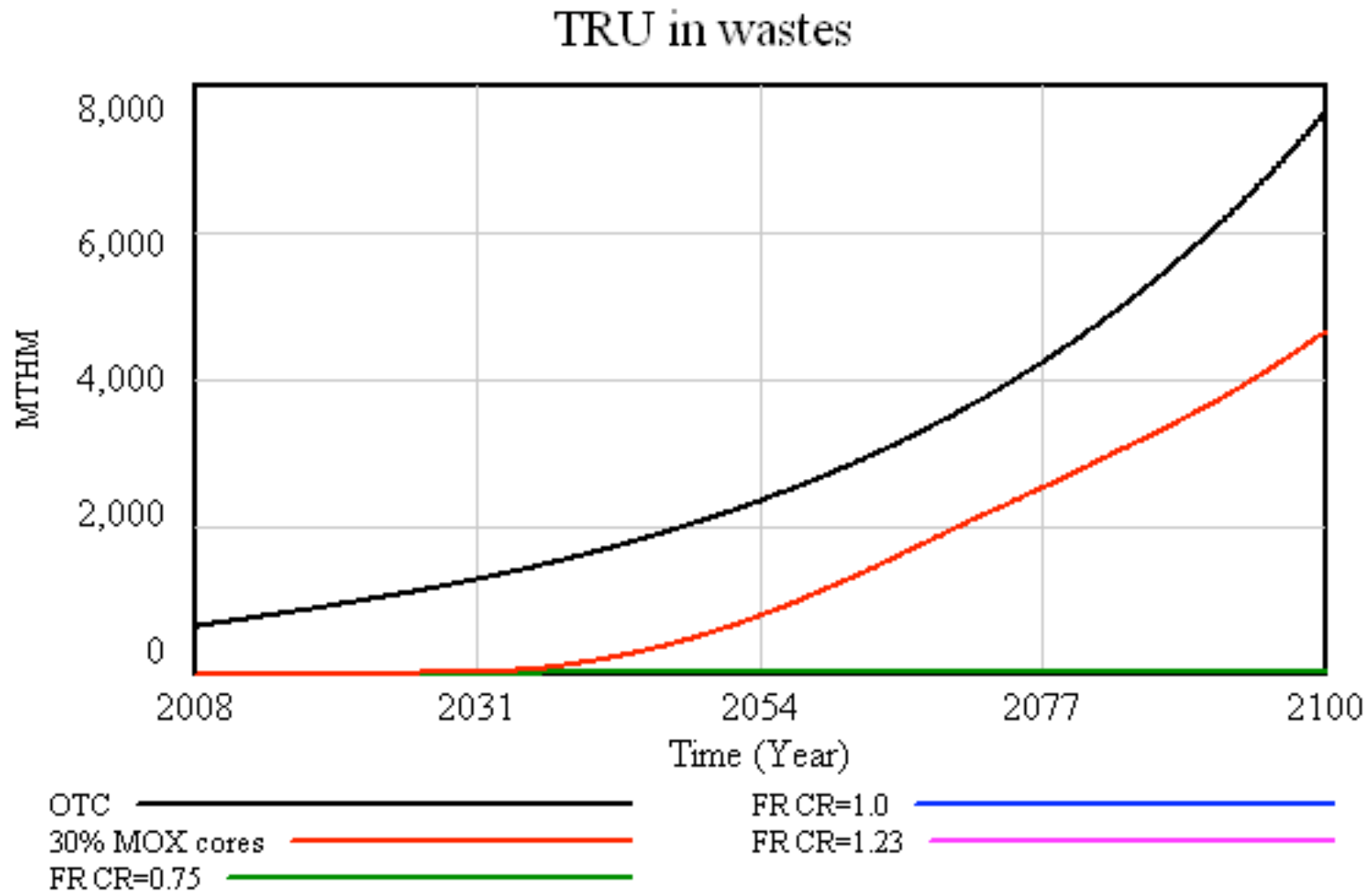


- **Compare two systems**
  - LWR with Am to repository
  - LWR + FR with Am burning but large Am inventory in reactor because of slow burn rate
- **Chart shows the relative Am inventory of the two systems if shut down nuclear system in Y years**
- **At 254 years, total fast reactor Am inventory in burn system half that of no-burn system**
- **Proposals for faster-burn options**



# TRU in wastes for 2.5% case

Significant reduction of TRU to repository is possible via recycling



# Nuclear Glasses: contributors to decay heat

*(colis C2, source Andra)*

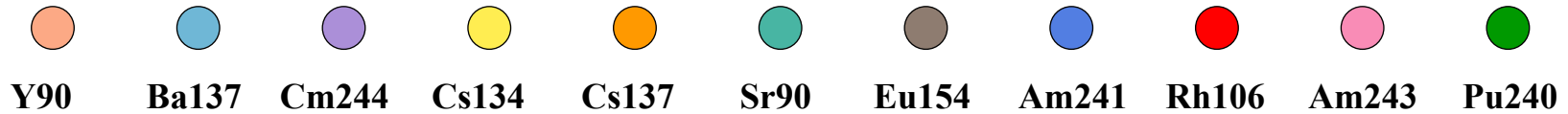
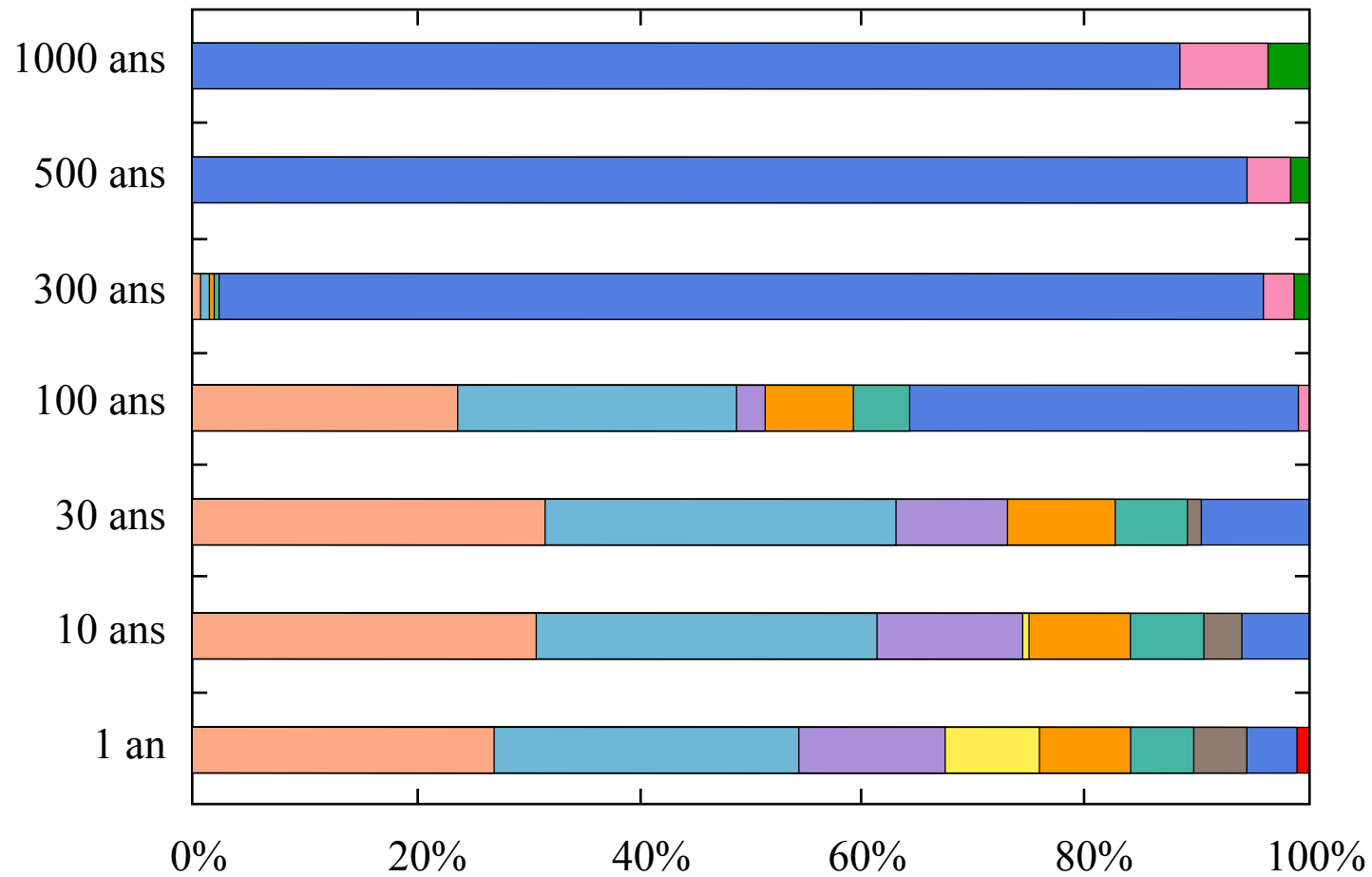


Image by MIT OpenCourseWare.

# Minimizing Waste via Advanced Actinide Recycling

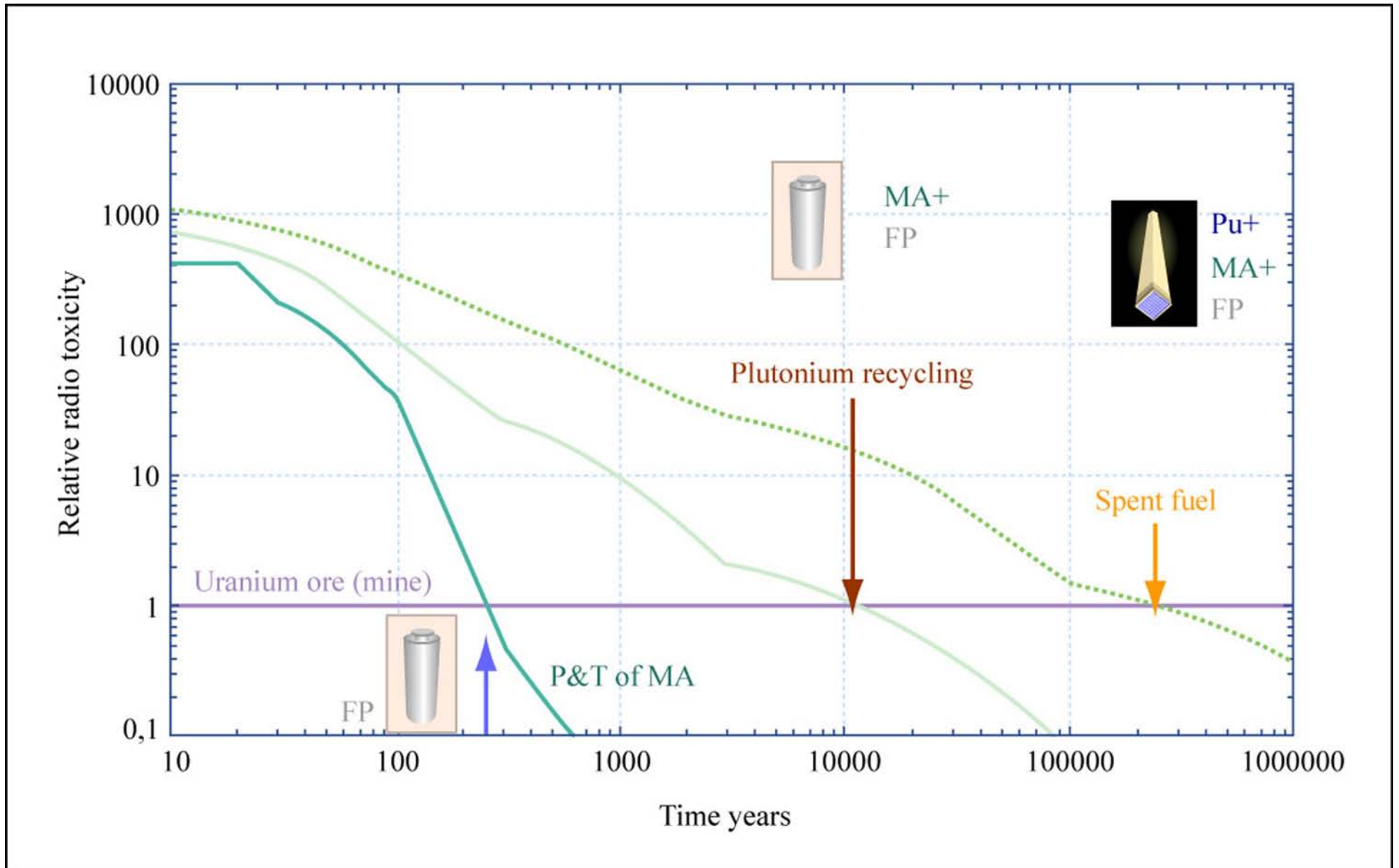
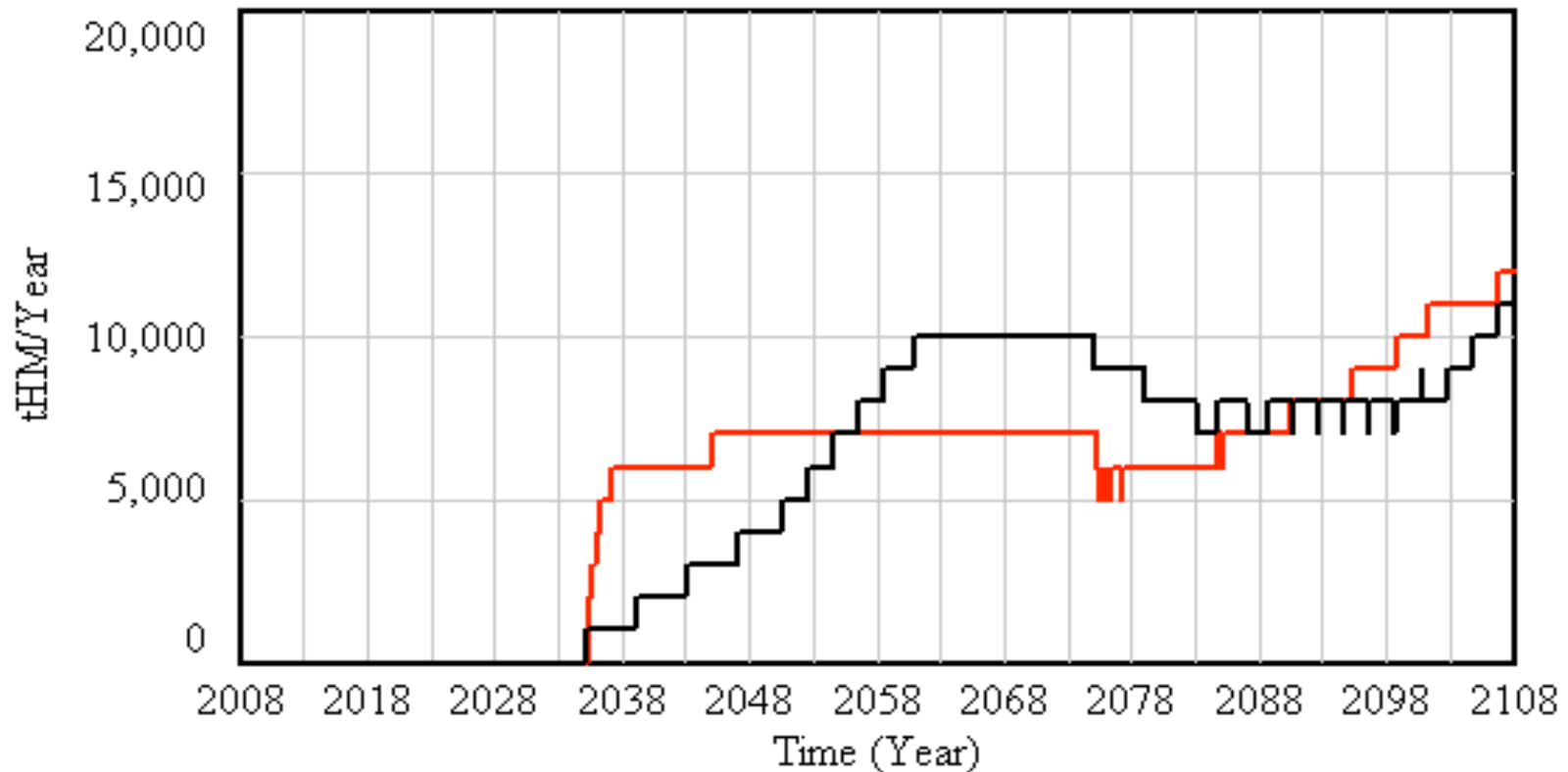


Image by MIT OpenCourseWare.

## Reprocessing Industrial Capacity

Capacity to Build Reprocessing facilities Will Have Dynamic Effects With A Time Constant of Decades

"Thermal" reprocessing capacity



Limited Industrial capacities

No limit on industrial capacities

# Advanced separation processes of actinides

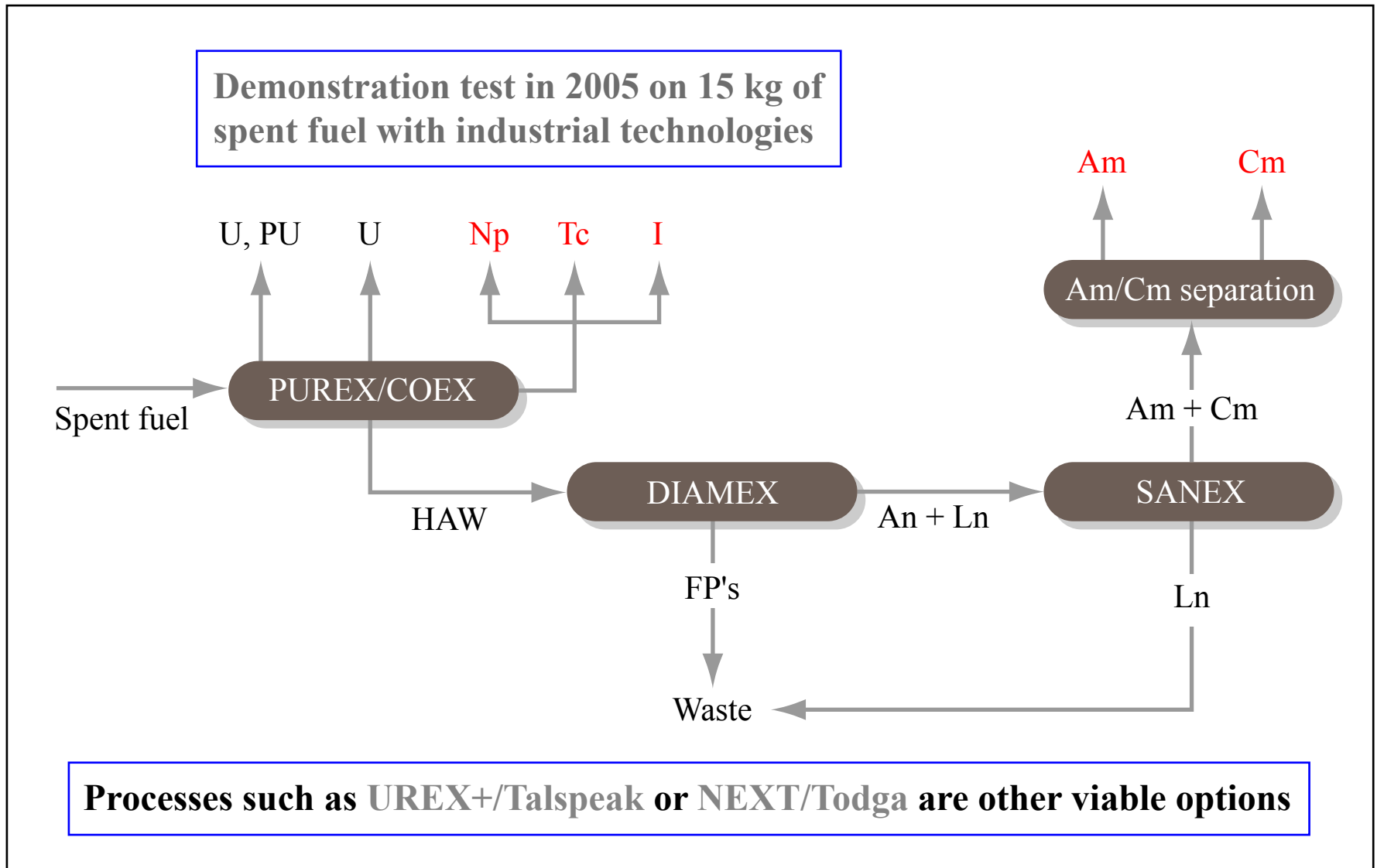
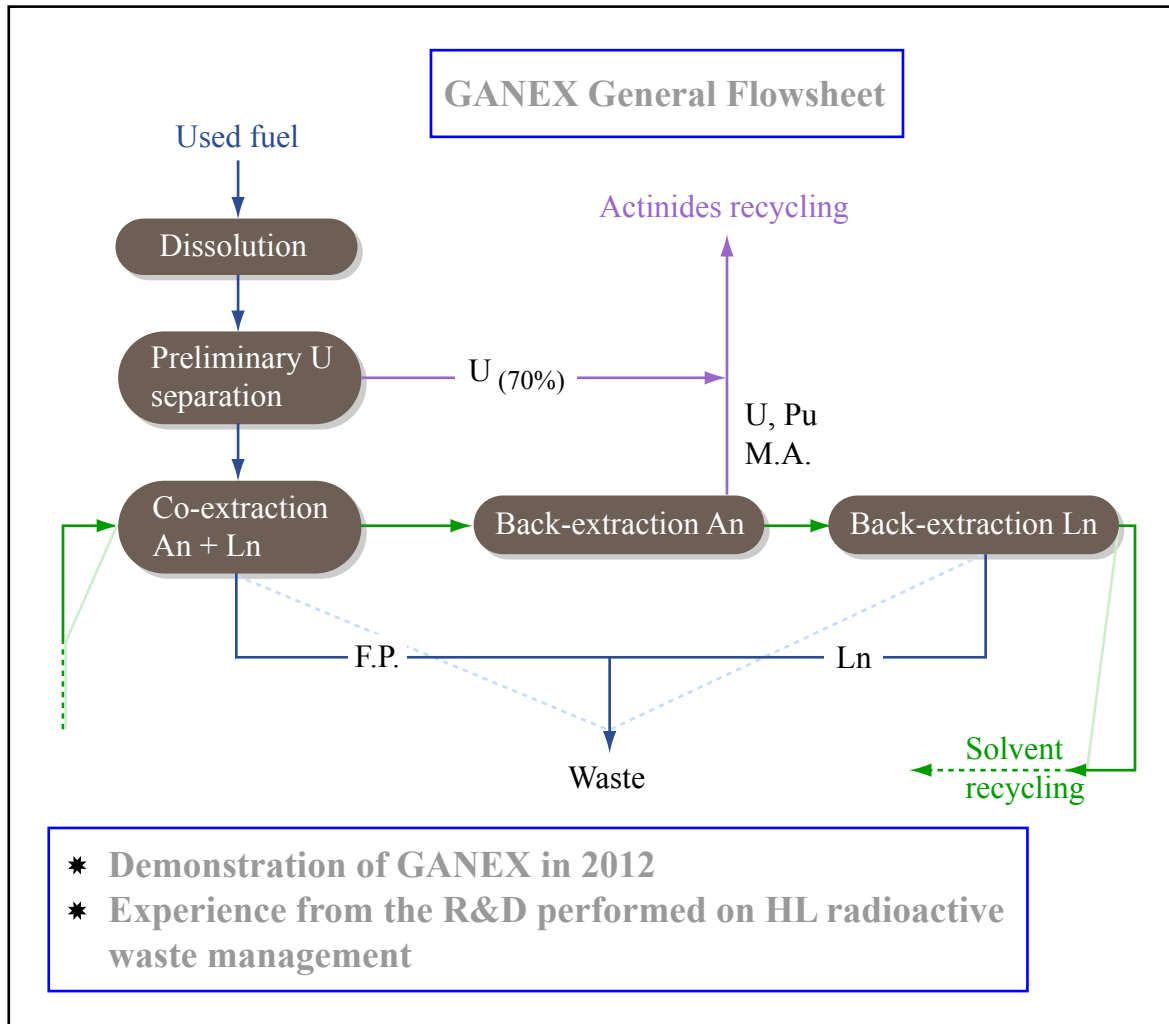


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# R&D on spent fuel separation processes



Co-conversion of actinides through the solgel process

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***Beads of U(VI)-Pu(IV) hydroxide gel***

Oxalic co-precipitation of actinides

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Image by MIT OpenCourseWare.

**(U,Np,Pu,Am) 78/1/20/1**

# What if we start fast reactors with medium enrichment uranium rather than plutonium?

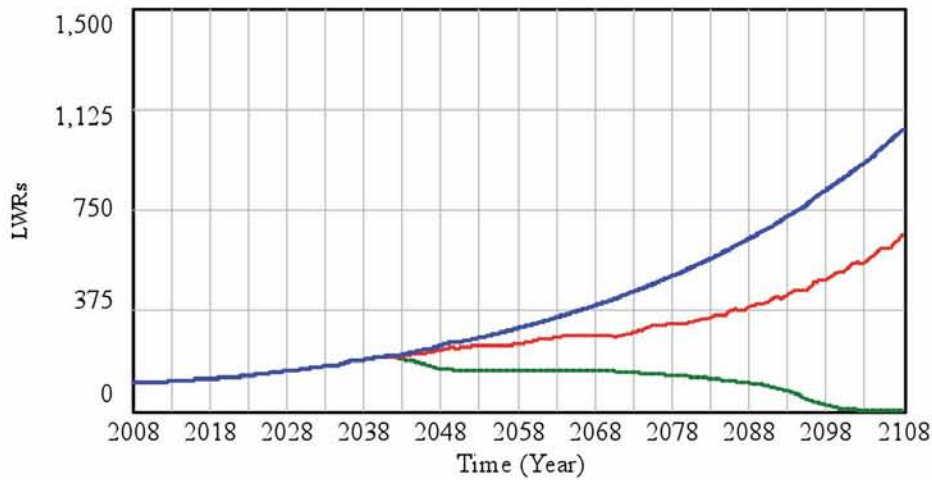
- Both EBR-II and Russian BN-60 were started with highly enriched uranium (about 60%).
- Cores were small and not optimized for U startup.
- Recent work at MIT (Prof. Driscoll and Dr. Shwageraus) indicate that medium enriched uranium (under 25%) startup is possible when an effective reflector is used (like MgO).

# Scenarios and Assumptions

	<b>Once Through</b>	<b>Basic FR – TRU startup</b>	<b>FR – enriched U startup</b>
Description	All LWR	LWRs and FRs built throughout the simulation; only TRU is used for FR startup	FRs are built starting in 2040 and no more LWRs are built; only 19% enriched U is used for FR startup
Uranium Enrichment	4.2% (LWR)	4.2% (LWR)	19% (FR)
FR introduction date	never	2040	2040
LWR building stops	never	never	2040
Thermal Reprocessing start	never	2040	never
Fast Reprocessing Start	never	2058	2058
Growth 2008-2020	1.7% per year		
Growth 2020-2138	2.5% per year		

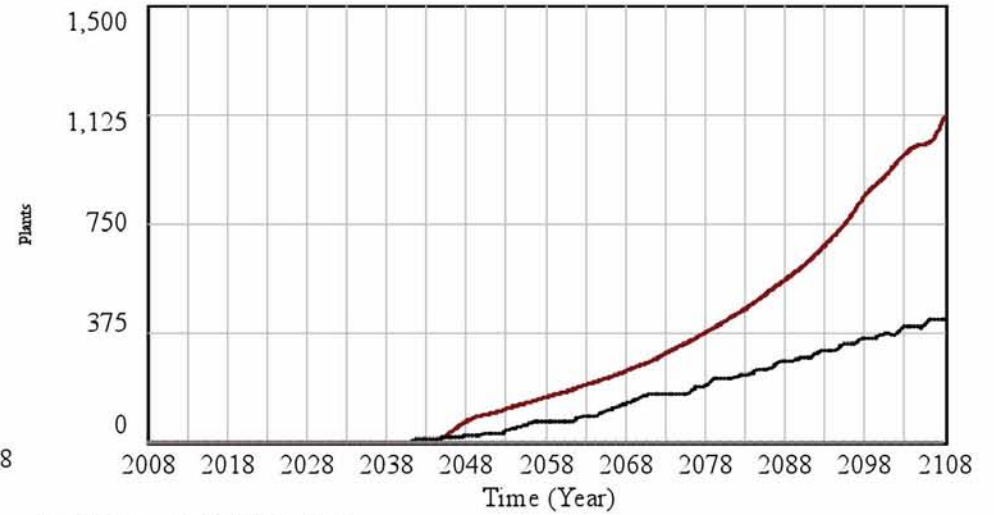


LWR : fleet in operation



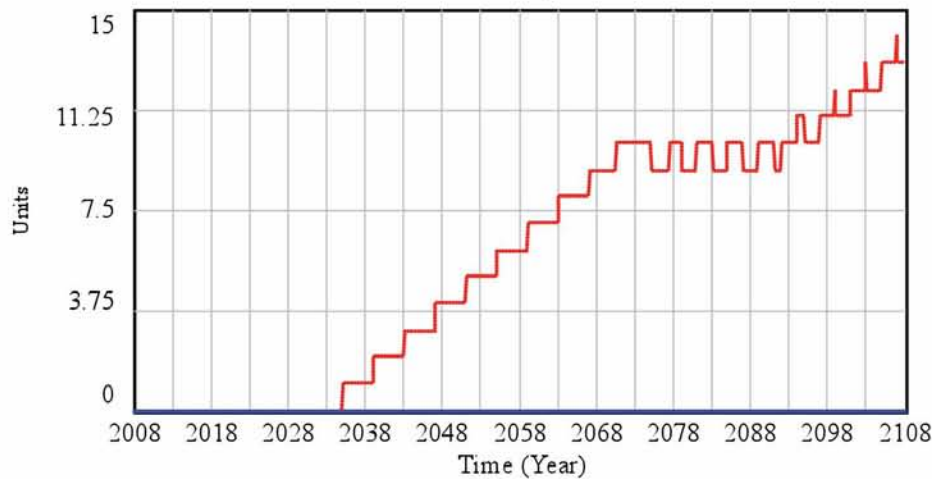
"LWR : fleet in operation" : OnceThru3  
 "LWR : fleet in operation" : Basic LWR + FR at 2040  
 "LWR : fleet in operation" : Enriched Uranium Startup

FR : fleet in operation



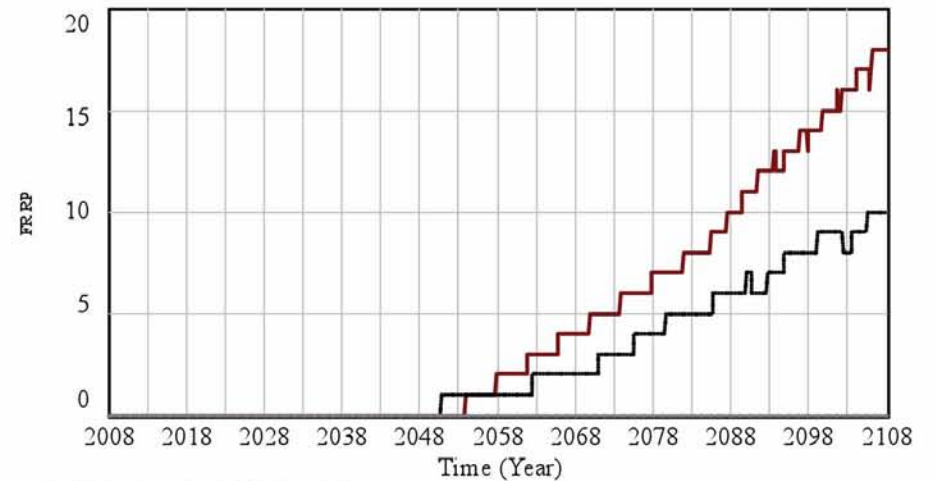
"FR : fleet in operation"[FR10] : OnceThru3  
 "FR : fleet in operation"[FR10] : Basic LWR + FR at 2040  
 "FR : fleet in operation"[FR10] : Enriched Uranium Startup

ThRP : fleet in operation



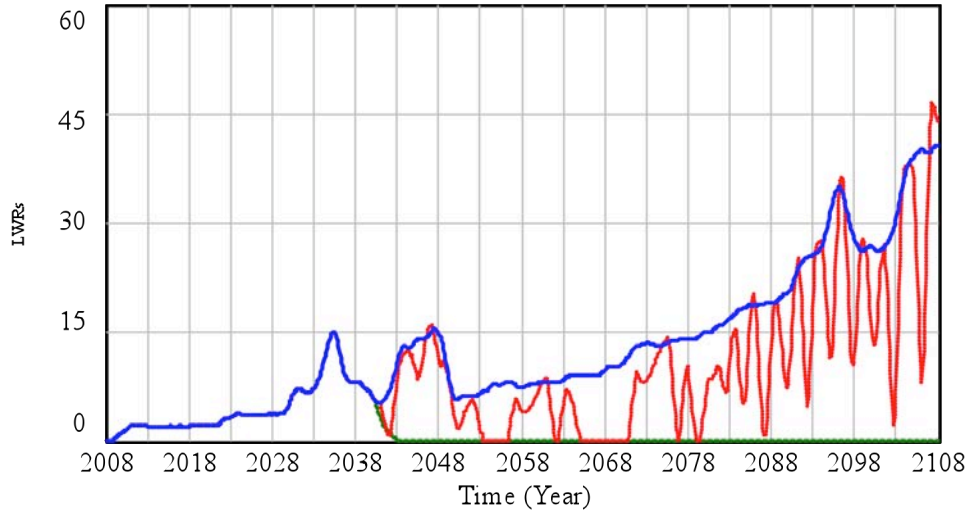
"ThRP : fleet in operation" : OnceThru3  
 "ThRP : fleet in operation" : Basic LWR + FR at 2040  
 "ThRP : fleet in operation" : Enriched Uranium Startup

FR RP : fleet in operation



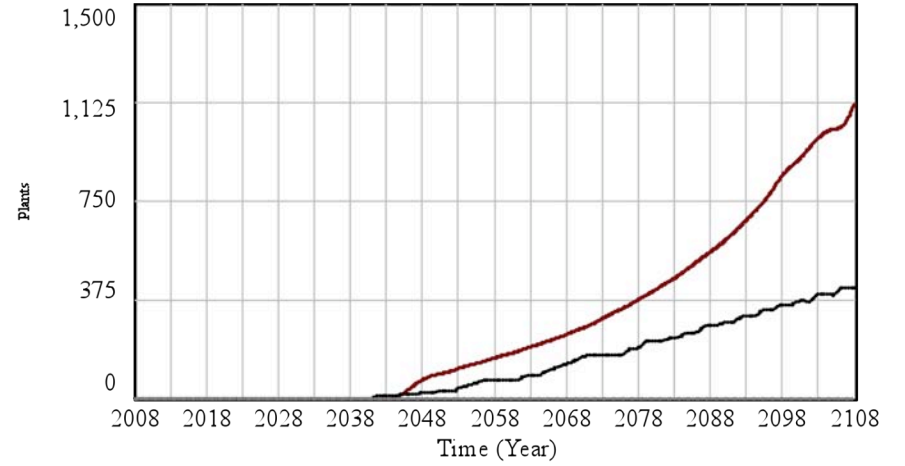
"FR RP : fleet in operation"[FR10] : OnceThru3  
 "FR RP : fleet in operation"[FR10] : Basic LWR + FR at 2040  
 "FR RP : fleet in operation"[FR10] : Enriched Uranium Startup

### LWRs Starting Commercial Operation



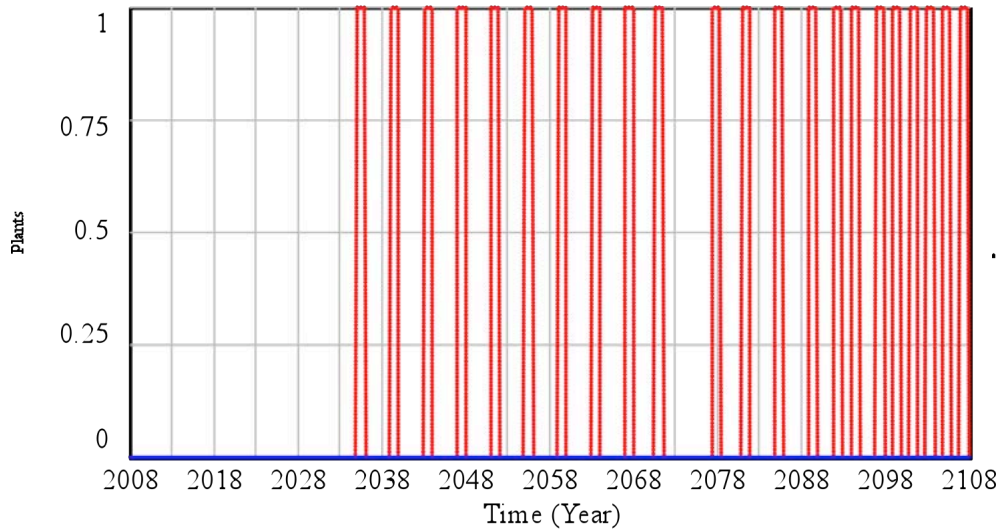
LWRs Starting Commercial Operation : Once Thru3 —————  
 LWRs Starting Commercial Operation : Basic LWR + FR at 2040 —————  
 LWRs Starting Commercial Operation : Enriched Uranium Startup —————

### FR : fleet in operation



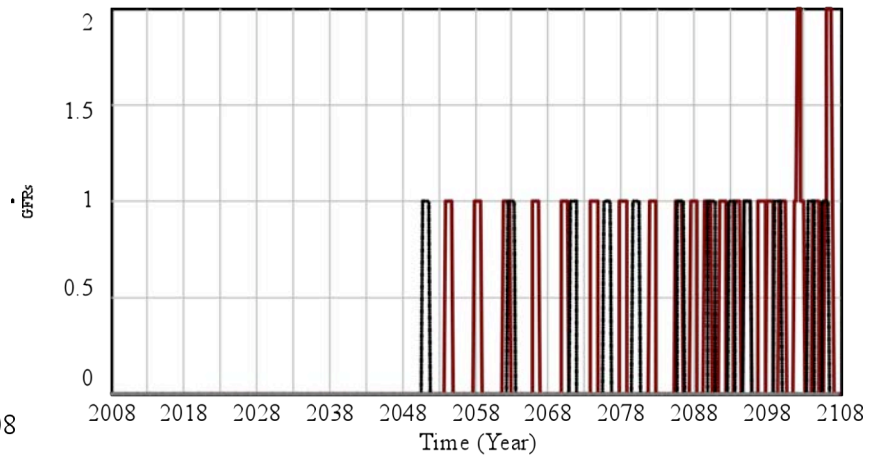
"FR : fleet in operation"[FR10] : Once Thru3 —————  
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 "FR : fleet in operation"[FR10] : Enriched Uranium Startup —————

### ThRPs Starting Commercial Operation per Year



ThRPs Starting Commercial Operation per Year : Once Thru3 —————  
 ThRPs Starting Commercial Operation per Year : Basic LWR + FR at 2040 —————  
 ThRPs Starting Commercial Operation per Year : Enriched Uranium Startup —————

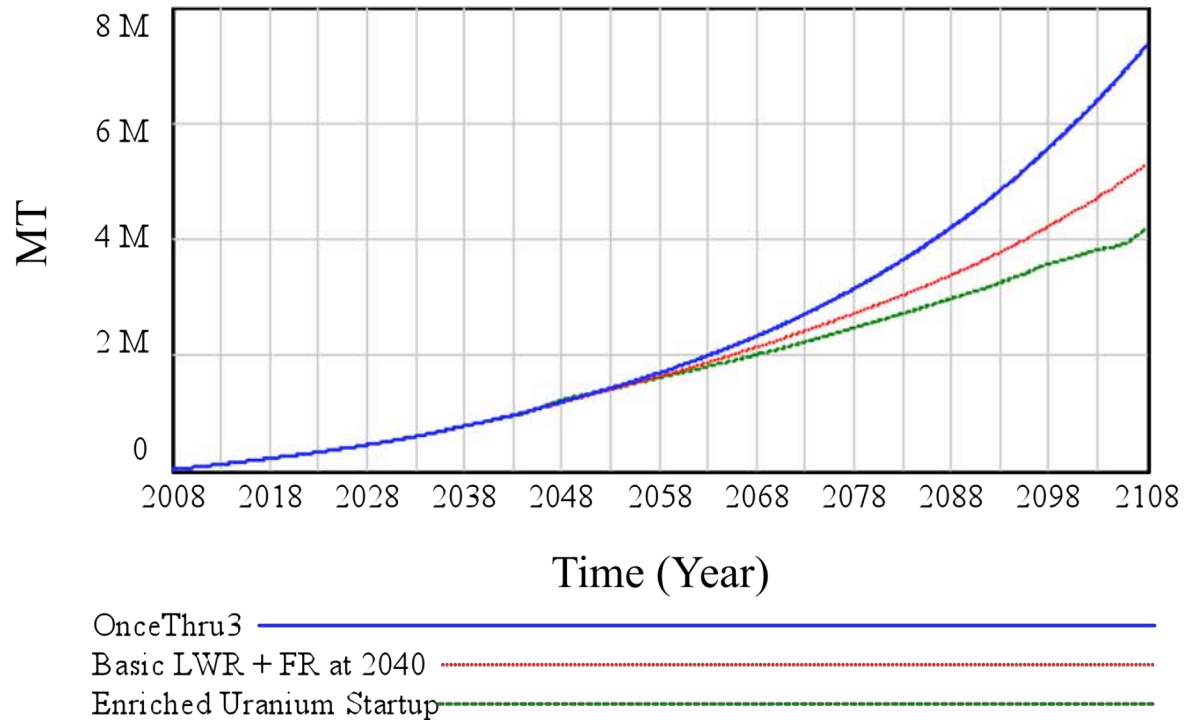
### FR RPs Starting Commercial Operation per Year



FR RPs Starting Commercial Operation per Year[FR10] : Once Thru3 —————  
 FR RPs Starting Commercial Operation per Year[FR10] : Basic LWR + FR at 2040 —————  
 FR RPs Starting Commercial Operation per Year[FR10] : Enriched Uranium Startup —————

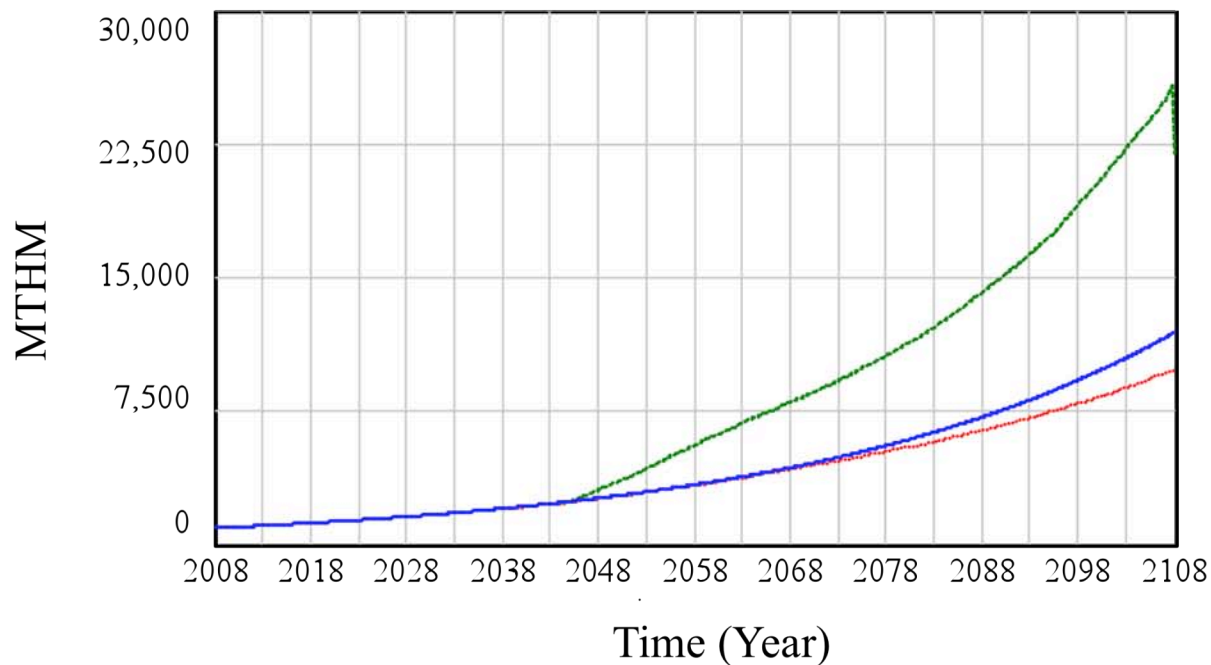
# Uranium Requirements for LWRs and for FR startup

Cumulative Natural Uranium Required over Simulation



# TRU in the System

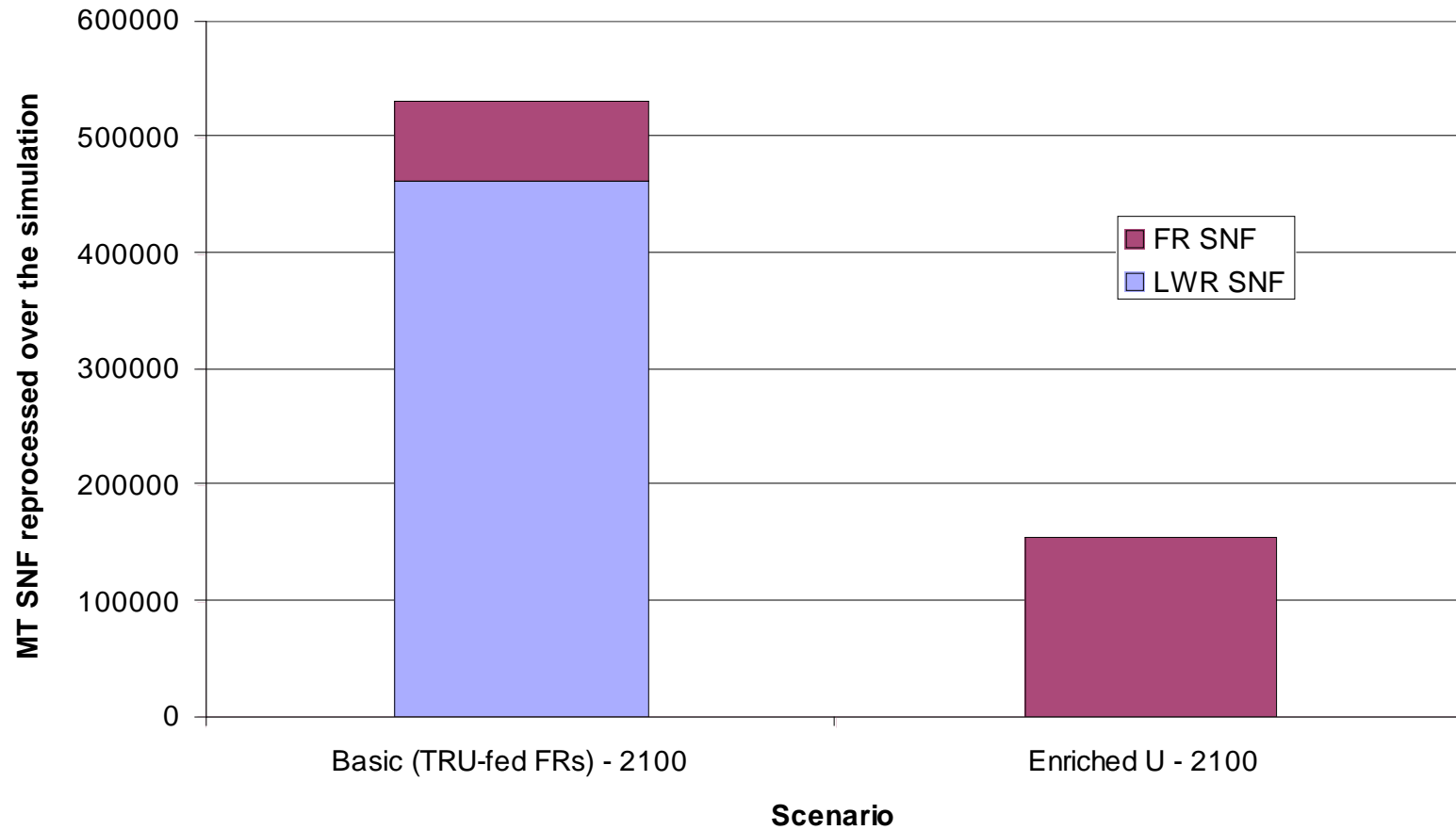
TRU: Total mass in the system (storage+plants+repository)



"TRU: total mass in the system (storage +plants+repository)" : Once Thru3  
"TRU: total mass in the system (storage +plants+repository)" : Basic LWR + FR at 2040  
"TRU: total mass in the system (storage +plants+repository)" : Enriched Uranium Startup

The Enriched U scenario has the most in-system TRU because TRU is continually recycled in the Fast Reactors

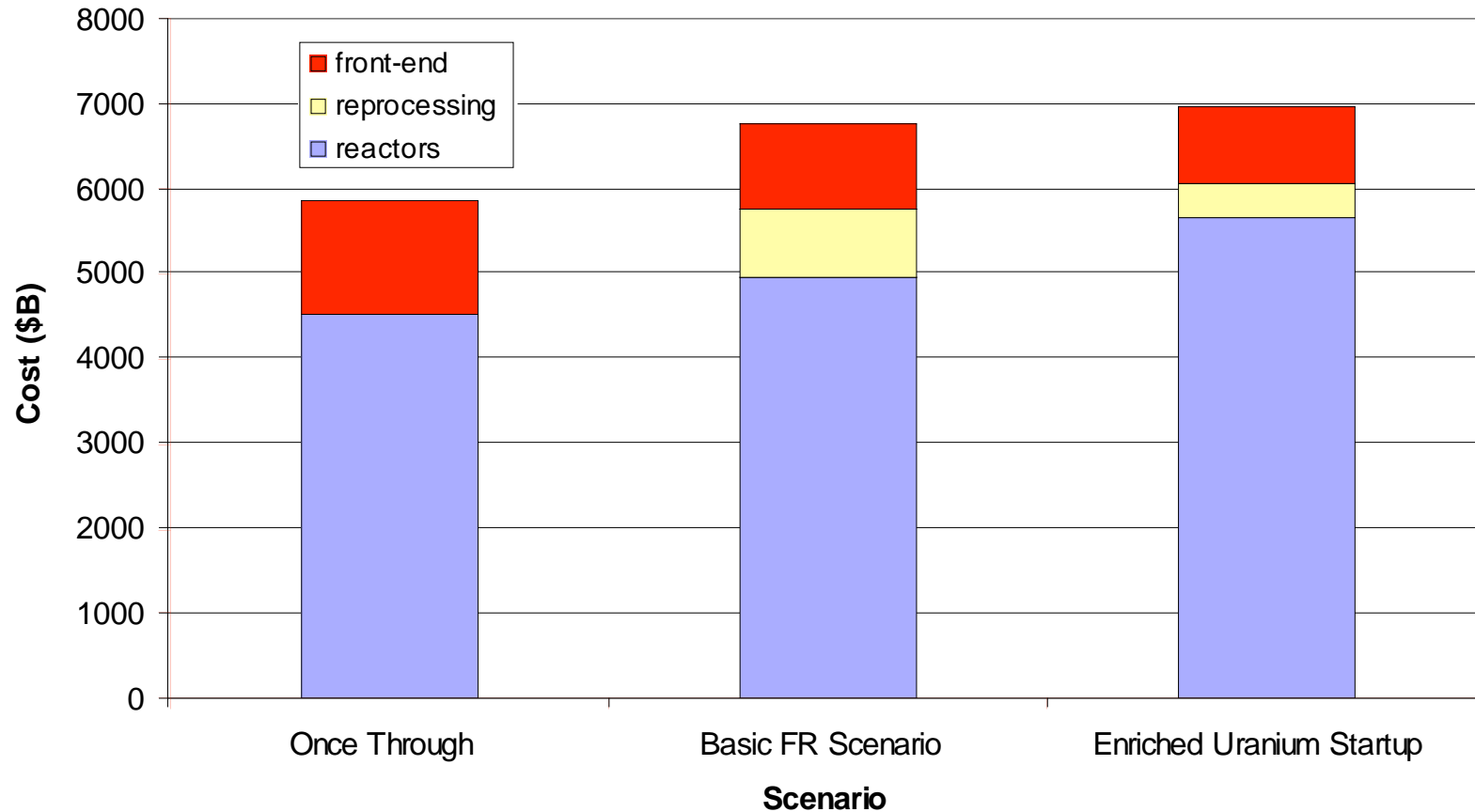
## Amounts of SNF Reprocessed



Shows how LWR spent fuel has much less energy by mass than FR spent fuel

# Basic Cost Calculation

Costs at 2100 for Constructed Reactors and Reprocessing



Front-End Fuel Cycle Costs+ Levelized Cost of Reprocessing + Capital Cost of Reactors

CAPITAL COSTS: LWR = \$4645 M/GWe, FR = \$5573 M/GWe

# Conclusions -1

1. The controlling factors in the transition to recycling are
  - *Rate of demand growth*
  - *Availability of transuranics (TRU) from discharged fuel*
  - *A smaller role for industrial capacity for FR fuel recycle and manufacture*
2. Starting recycling with bred fuel (Pu or TRU) is constrained by availability from spent fuel of LWRs and advanced reactors
  - *LWRs will play a major role in nuclear energy for the entire century.*
  - Self-sustaining reactors, with conversion ratio of about 1.0, impose the minimum requirement for recycling facilities, and thus provide well paced penetration of the system.
  - Fast reactors with conversion ratio higher than one (breeder reactors) do not allow much faster penetration, as breeders demand more TRU fuel in the core and require more frequent processing.
  - *U235 fueled fast reactors can aid in breeder penetration.*

# Conclusions - 2

## 3. Recycling will have limited impact on natural uranium consumption in this century:

- MOX use starting in 2025 will have little impact (less than 10% if only Pu or TRU are used, less than 20% if U is also recycled)
- Fast reactors starting in 2040 lead to about 35% reduction in the demand for natural uranium.
- Fast reactor conversion ratio beyond one does not always lead to better results than a conversion ratio of just one.

## 4. Recycling does not lead to appreciable reduction of TRU in total energy system but leads to significant reduction in the amount of TRU destined to the repository.

- Recycling can greatly affect amount of very long lived higher actinide in the waste, but not fission products. (i.e. no effect on short term heat load or long term dose due to water migration).
- Depending on separation process choice, significant waste streams may result, adding to cost and limiting motivation for a closed fuel cycle in the absence of substantial growth in nuclear energy utilization.



# Conclusions - 3

5. We have time until before recycling and disposal technology be truly required, and we must use the time to develop more appealing options.
  - Dry storage is a reliable and safe option for storing the spent fuel for decades
  - All spent fuel from the 100 reactors if operated for 60 years can be stored on 300 acres
  - Studies of disposal options have been prohibited for 25 years, and a second look at some options is needed (e.g. deep bore holes for minor actinides)
  - Studies of more economic and uranium initiated fast self-sustaining reactors are to be pursued
  - System simulation studies to capture the effects of various options would be needed
  - Assisting the industry to move to much higher burnup fuel would be useful

# R&D Decline

Relative trends of government funded nuclear fission R&D data normalized to 1 in 1985

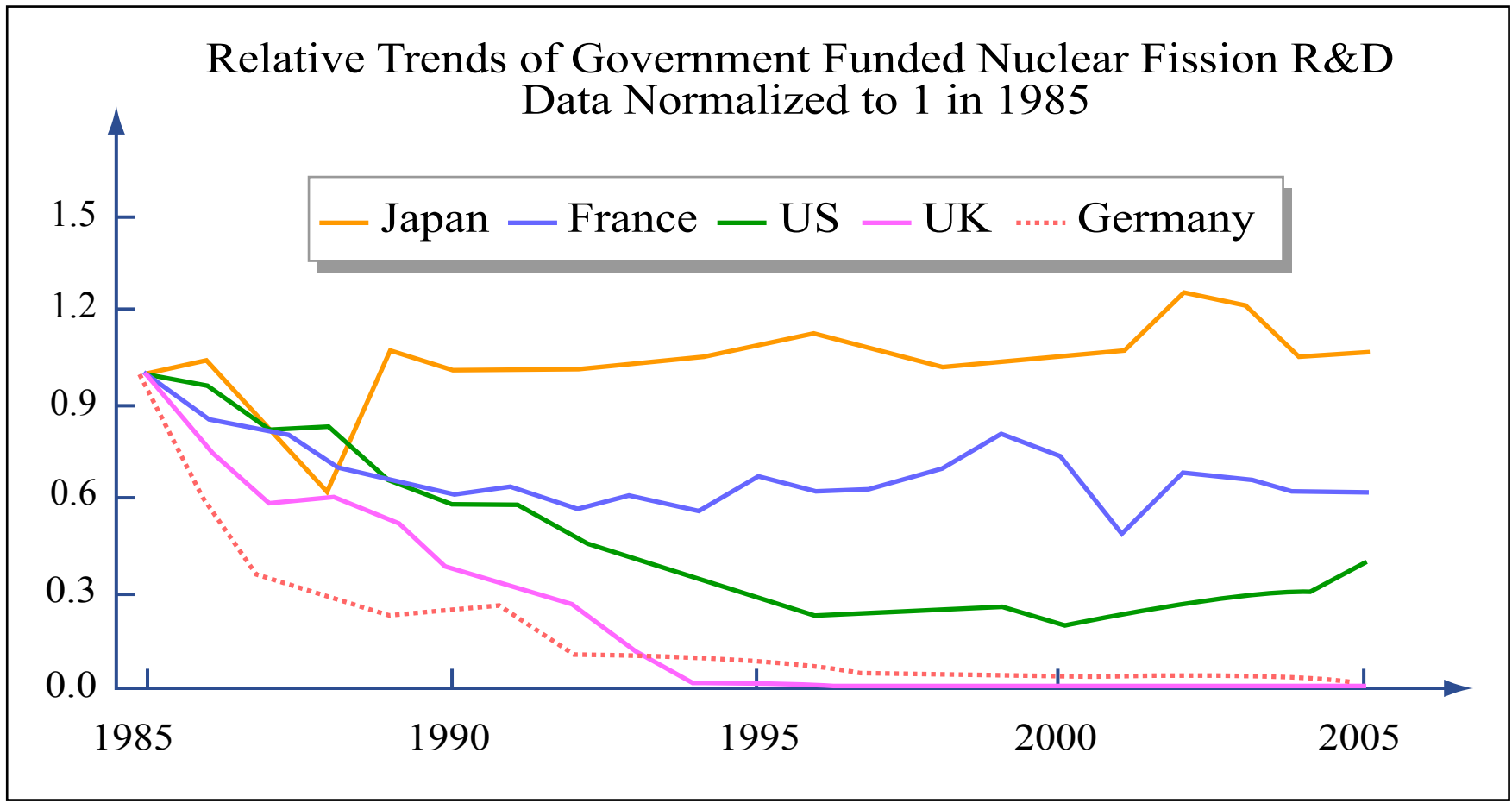
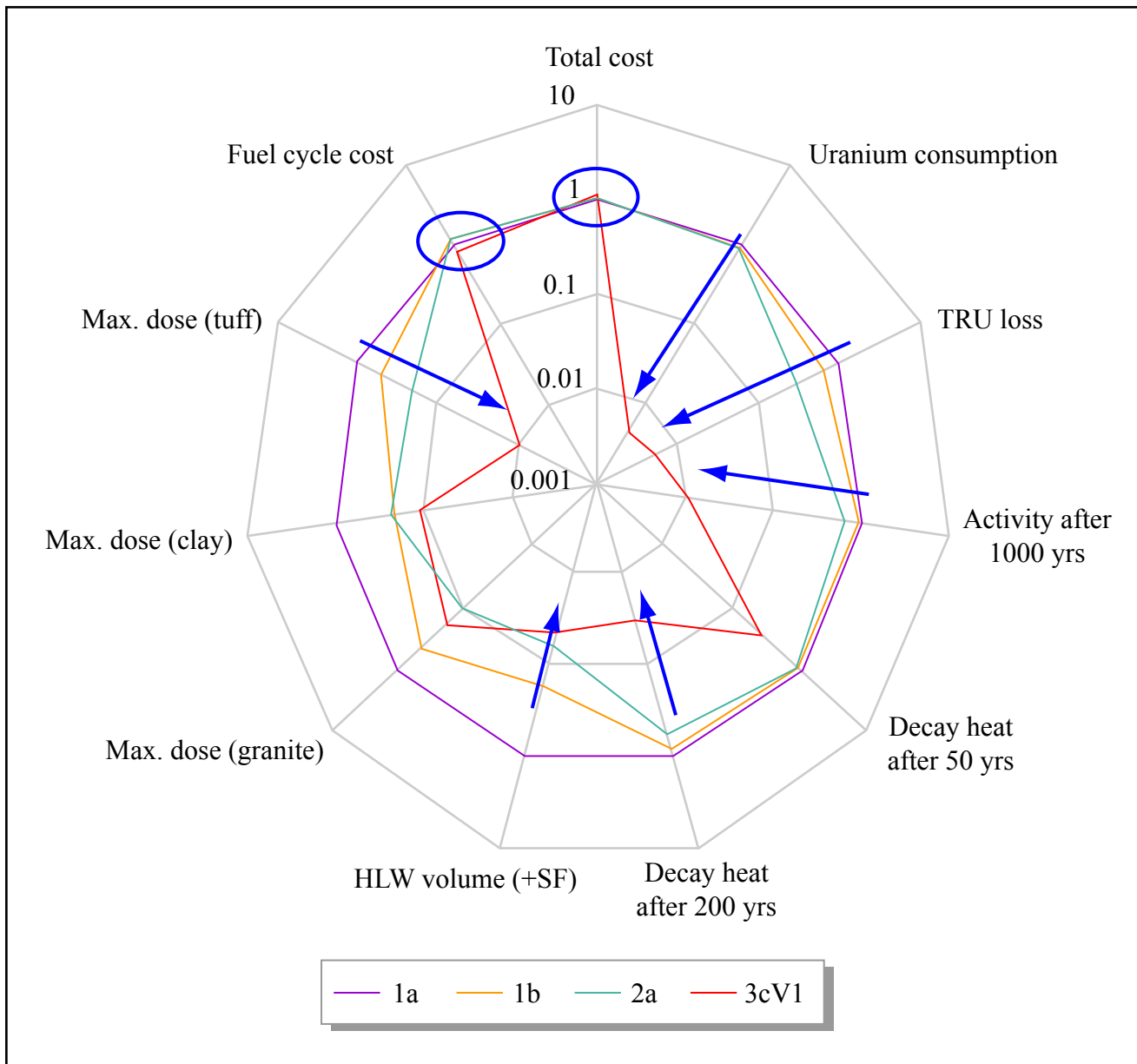


Image by MIT OpenCourseWare.

# NEA assessment of closed Fuel Cycles (ENC 2005)

## Impact of Gen IV Fast reactors + P&T



**1a: Once-through cycle as reference.**

**1b: Full LWR park, Pu re-used once**

**2a: Full LWR park, multiple re-use of Pu**

**3cV1: Full fast reactor park and closed fuel cycle (Gen IV).**

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