The Future of the Nuclear Fuel Cycle

An Interdisciplinary MIT Study

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For the next several decades, once through fuel cycle using light water reactors is the preferred economic option for the U.S.

- Accelerate implementation of first mover incentive program
- No shortage of uranium resources
- Scientifically sound methods to manage spent nuclear fuel (SNF)
- Resource extension and waste management benefits of limited recycling (MOX) are minimal
- Fuel cycle transitions take a long time: many LWRs and little difference in total transuranic inventories or uranium needs in this century in standard closed fuel cycle scenario

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Planning for long term managed storage of SNF – for about a century – should be integral for fuel cycle *design*

- Can and *should* preserve options for disposal, reprocessing, recycle
- Why? Major uncertainties for informed choices:
  - Societal: NP growth? Nonproliferation norms?...
  - Technical: fast or thermal reactors? Conversion ratio? Waste management benefits? SNF as resource or waste?...
- Start moving SNF from shut-down reactors
- Move to centralized managed storage: not for economics or safety

A key technical point: CR=1 sustainable and has advantages

- High CR constrains choices: Pu-initiated fast reactor
  - Rooted in uranium resource expectations

- Important technology choices made available with CR=1

  - “LEU” startup of fast reactor? SNF as waste? Saves uranium and lowers enrichment needs!

  - Thermal reactors for closed fuel cycle? Economics vs fast reactors?

Waste management: geological disposal needed for any choice

- Systematically develop geological disposal, with public process
- Integrate waste management with fuel cycle design: waste stream requirements as important as what's recycled to reactor
- Develop risk-informed waste management system: composition not source
- Establish quasi-government waste management organization with sufficient authorities – not recognizable in US program to date
  - Site selection in concert with governments/communities
  - Management of funds
  - Negotiate SNF/waste removal with owners
  - Engage policy/regulatory bodies on fuel cycle choices and waste
  - Continuity in management

Nonproliferation and the fuel cycle: principally institutional

- Actively pursue fuel leasing with financial incentives and fixed term renewable commitment
- Absence of waste management program constrains options
- Technology choices have some impact: e.g., U-fed fast reactor scenario reduces U enrichment needs in second half of century

Commercial nuclear technology introduction has a long time constant, calling for strong RD&D program now: about $1B/yr

- DOE 2010 roadmap a good start
- LWR R&D important/ e.g., innovation hub on advanced simulation
- About a third for research infrastructure
- Large scale demonstrations in time

MIT Future of the Nuclear Fuel Cycle Study

Uranium Resources and SNF Storage

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Uranium Resources

Finding:

There is no shortage of uranium that might constrain future commitments to build new nuclear plants for much of this century…

Recommendation

An international program should be established to enhance understanding and provide higher confidence in estimates of uranium costs versus cumulative uranium production

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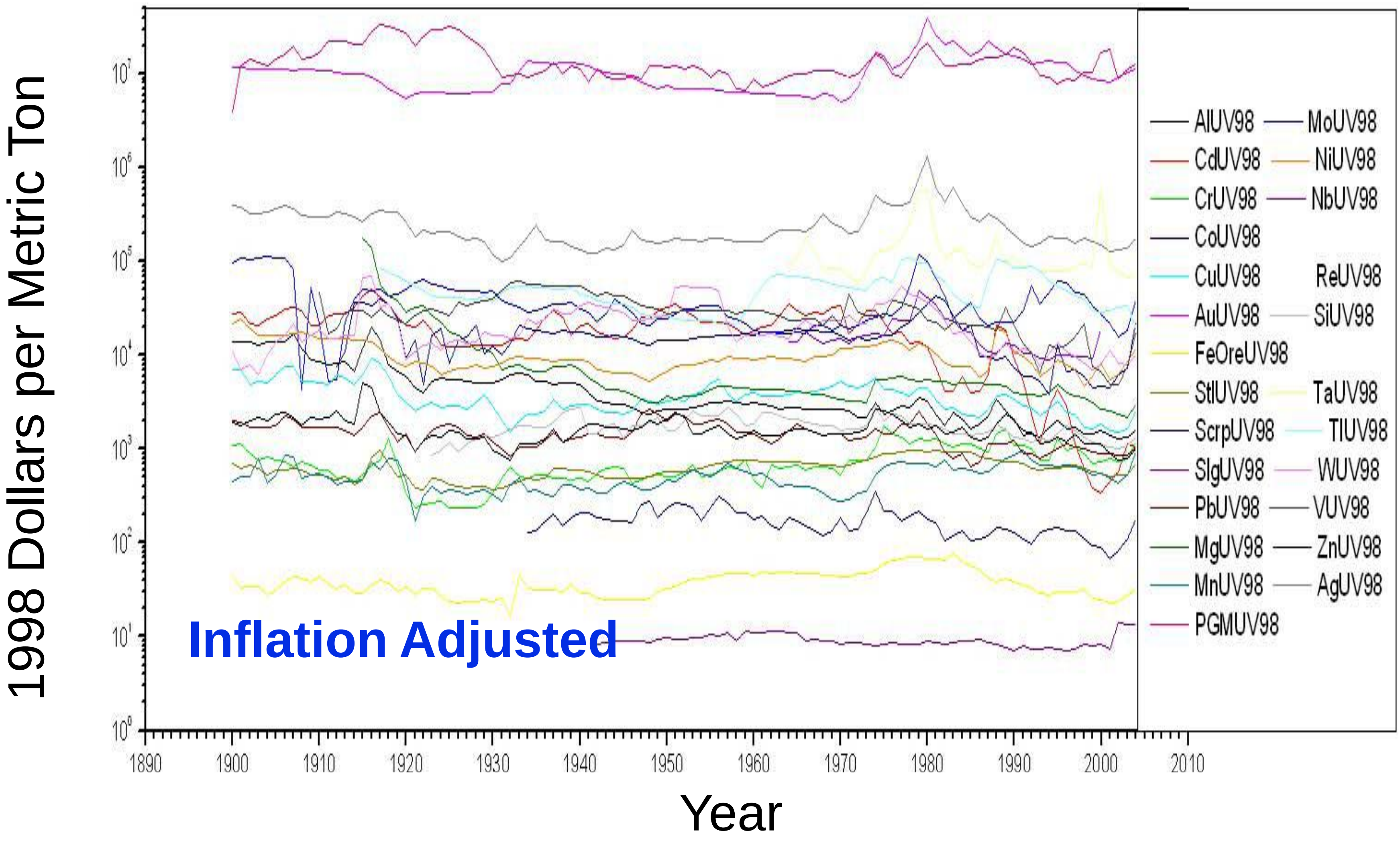
Uranium Cost Assessment

- Uranium needs
  - ~200 tons per year for a 1000-MW(e) nuclear reactor
  - 2 to 4% of the cost of nuclear electricity
  - Uranium prices have small impacts on electricity prices
- We evaluated the costs of uranium mining versus cumulative worldwide uranium production. Inputs:
  - Uranium resource estimates versus ore grade
  - Economics of scale
  - Technological learning over time
- Best estimate of 50% increase in uranium cost if:
  - Nuclear power grows by a factor of 10 worldwide
  - Each reactor operates for a century

Prices of 25 Metals Over a Century

Uranium is a Metal: Similar Cost Trends For Most Metals



Spent Nuclear Fuel Management

Finding

SNF storage reduces repository costs and performance uncertainties. Fuel cycle transitions require a half century or more. Storage provides time to decide whether LWR SNF is a waste or resource

Recommendation

Planning for long term interim storage of spent nuclear fuel—on the scale of a century—should be an integral part of nuclear fuel cycle design

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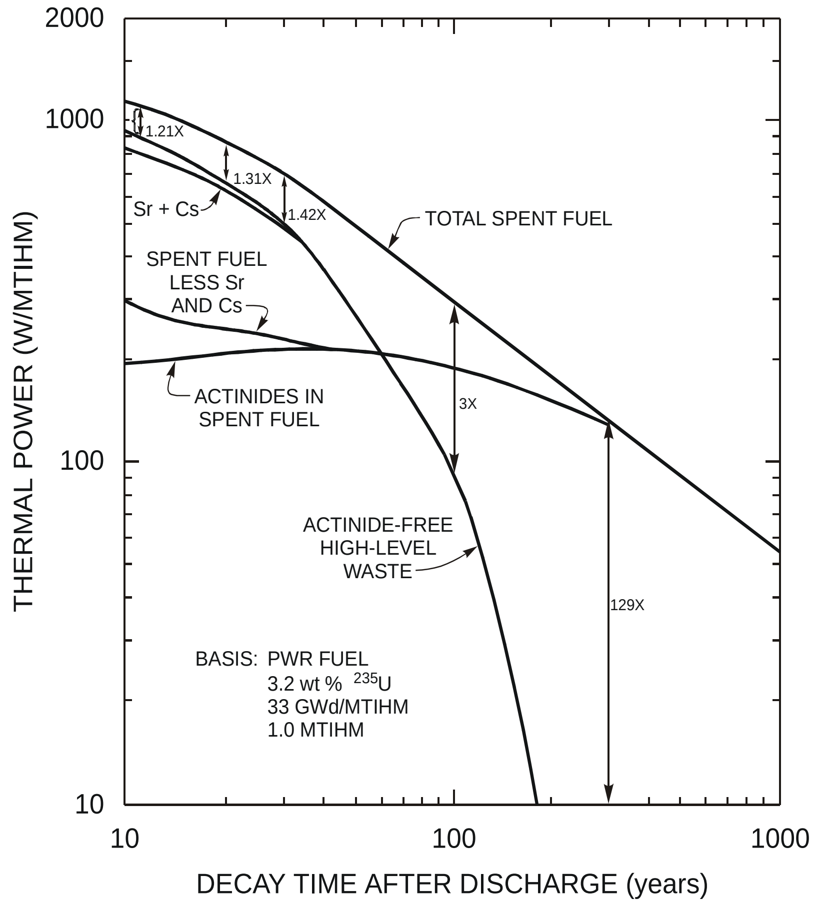
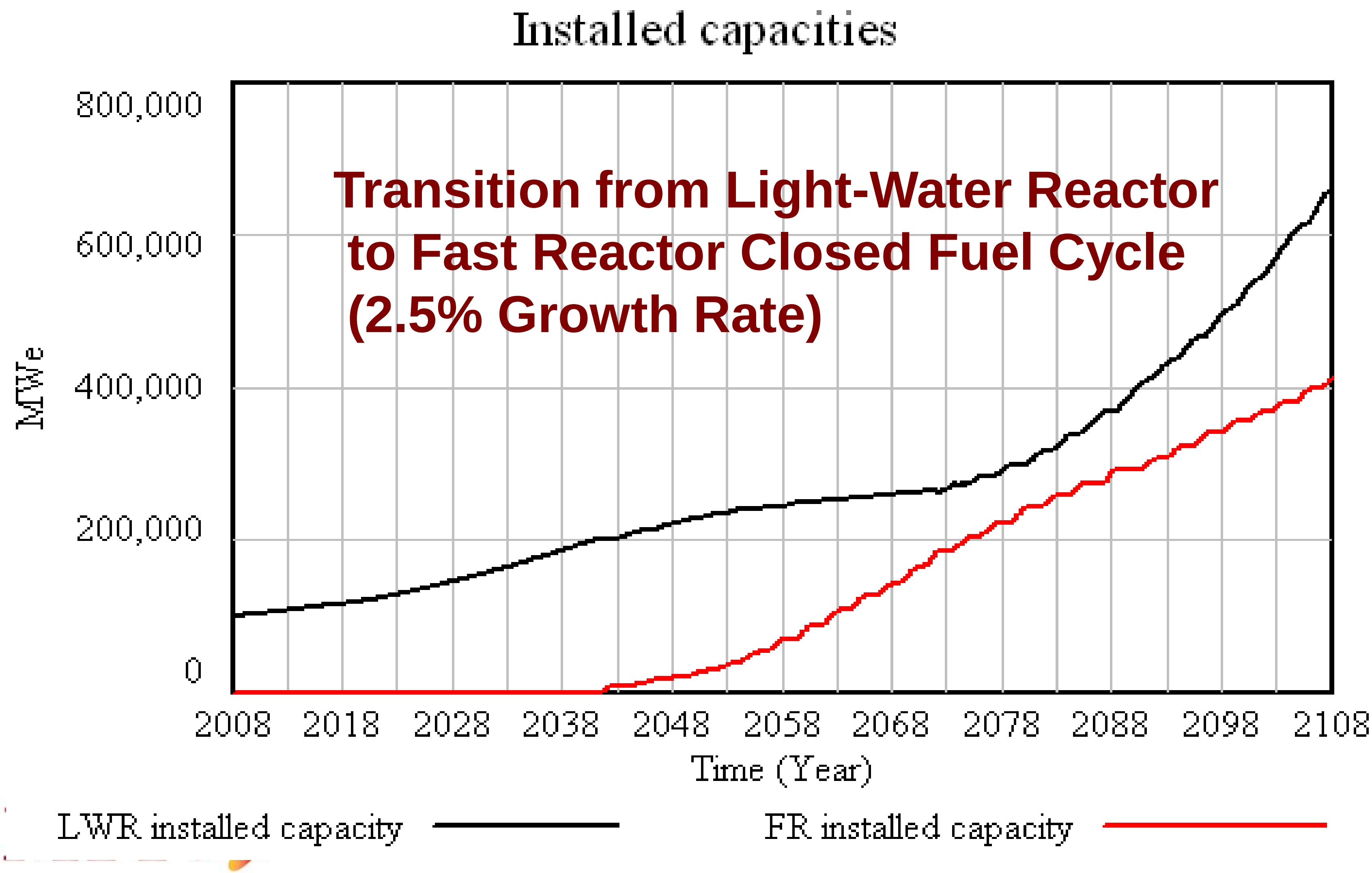
Repository Programs Store SNF to Reduce Repository Size, Cost, and Performance Uncertainties

- Decay heat decreases with time, planned storage times are 40 to 60 years
- Sweden and France built SNF storage facilities in the 1980s for this purpose
- Proposed U.S. YMR had implicit storage system
  - Fill repository over 30 years
  - Operate ventilation for 50 additional years—long-term storage



It Takes 50 to 100 Years for Fuel Cycle Transitions



It Will Be Decades Before We Know If LWR SNF Is a Resource or Waste

- LWR SNF has a high energy content
  - Equivalent to super “Strategic Petroleum Reserve”
- LWR SNF could be a waste
  - Alternative strategies to start fast reactors with sustainable fuel cycles using low-enriched uranium
  - Alternative strategies may have lower costs

SNF at Decommissioned Sites

Finding:

The burden of SNF storage is small at an operating site… This is not true for decommissioned sites where there are no longer the normal reactor operations associated with SNF handling, storage, and security. SNF storage limits reuse of these sites

Recommendation

We recommend that the U.S. move toward centralized SNF storage sites—starting initially with SNF from decommissioned sites and in support of a long-term SNF management strategy

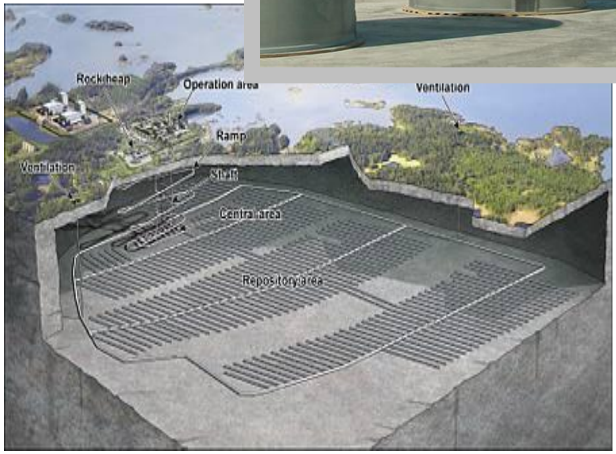
SNF Storage Options

Finding:

Either distributed storage (at reactor), centralized long-term storage, or storage in a repository is technically sound

Recommendation

An RD&D program should be devoted to confirm and extend the safe storage and transportation period



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Systems Analysis: Fuel Cycle Options and Outcomes

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Briefing on MIT Study on Future of the Nuclear Fuel Cycle
Center for Strategic and International Studies

Dynamic Simulation of the Nuclear Energy System

Objective:

Examine implications of a reasonable range of nuclear energy growth rates in the US on various nuclear fuel cycle options over this century.

Key Questions:

- How would various fuel cycle options impact demand for nuclear fuel, mined or recycled?
- What is the impact of introducing recycling on the amounts of stored spent fuel, TRU and wastes to be sent to repositories?
- What parameters have the largest impact on demand for U, fuel cycle industrial infrastructure and spent fuel storage needs?

Fuel Cycle Options

Base cases in red italics

Once Through:

Build ALWR/ Current Burnup (50 MWD/kg)

Limited Thermal Reactor Recycle:

PUREX-based one time recycling of U-Pu as mixed oxides (MOX) to LWRs

Fast Reactor Recycle of all transuranics, TRU(metallic fueled reactors studied by ANL and GE):

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

TRU recycle in fast burner ABR (with low CR = 0.75)

TRU recycle in fast breeder FBR (with CR = 1.23)

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Other cycle options have been considered.

Fuel Cycle Key Assumptions

- Nuclear power will grow to 115 GWe by 220; after 2020 at rates 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
  - 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 reprocessing, and 1 yr of fuel manufacturing.
  - Minimum lifetime capacity factor of recycling plant is 80%.
  - LWR fuel recycling plant size: 1000MT/yr, can be added every 4 years prior to 2050, 2 years after 2050.
  - FR recycling plant size 200MT/yr for burners and 500MT/yr for breeders; can be added every 2 years prior to 2050, then every 1 year
  - U is recycled for all options.

Installed Capacity in GWe

LWRs will play a major role throughout this century
Fast reactor conversion ratio beyond 1.0 may not be helpful

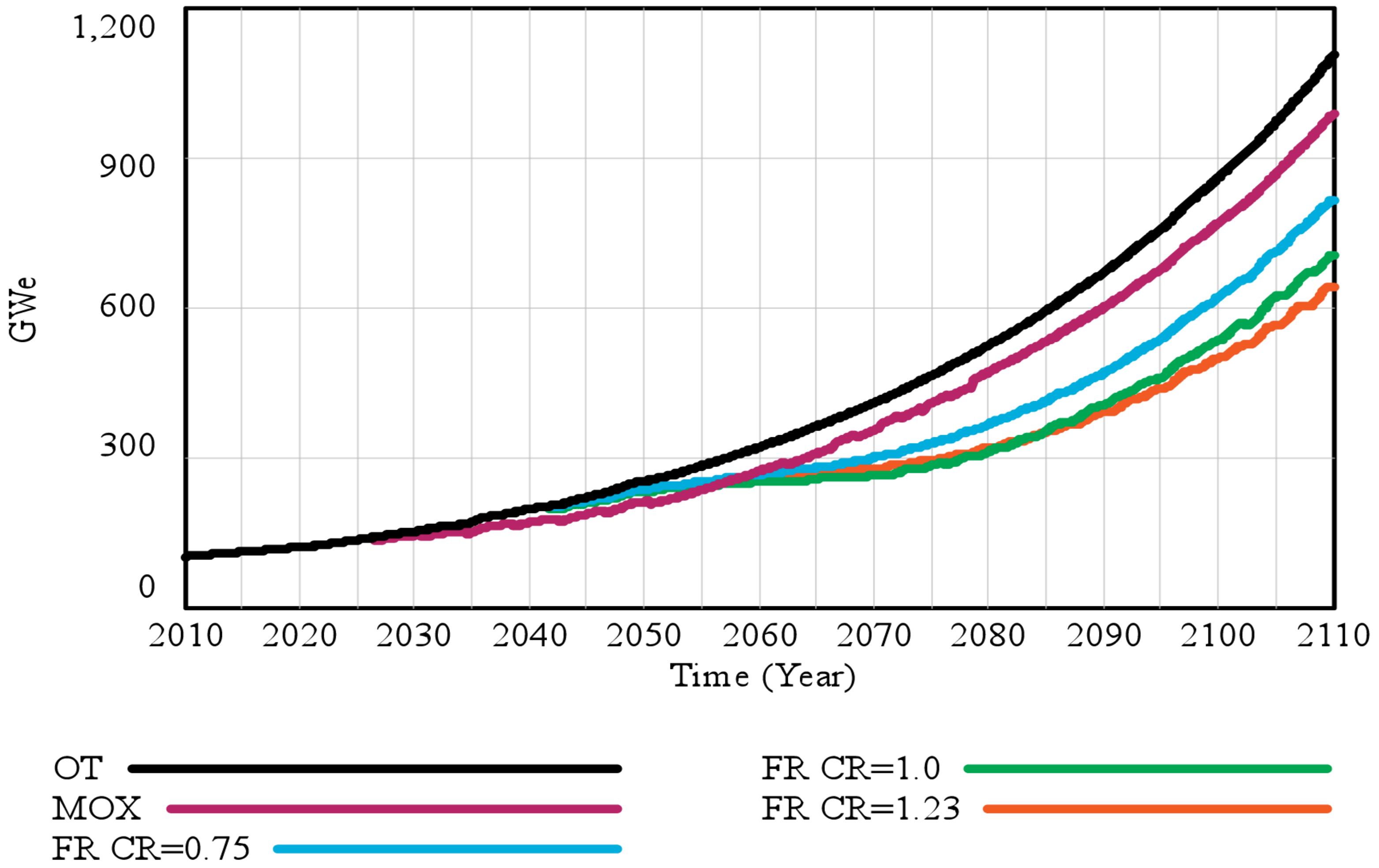
Growth Rate	Fuel Cycle	By 2050	By 2100
1.0%	OTC	166	269
	MOX	41	32
	FR*	20;22; 20	234; 236; 234
2.5%	OTC	250	859
	MOX	41	91
	FR*	20; 23; 21	259; 345; 391
4.0%	OTC	376	1,001**
	MOX	41	117
	FR*	20; 23; 21	400; 521; 540

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

Installed LWR Capacity

for the 2.5% growth case

LWR with once through fuel cycle will grow under all options



Cumulative Demand for Uranium (1M MT)

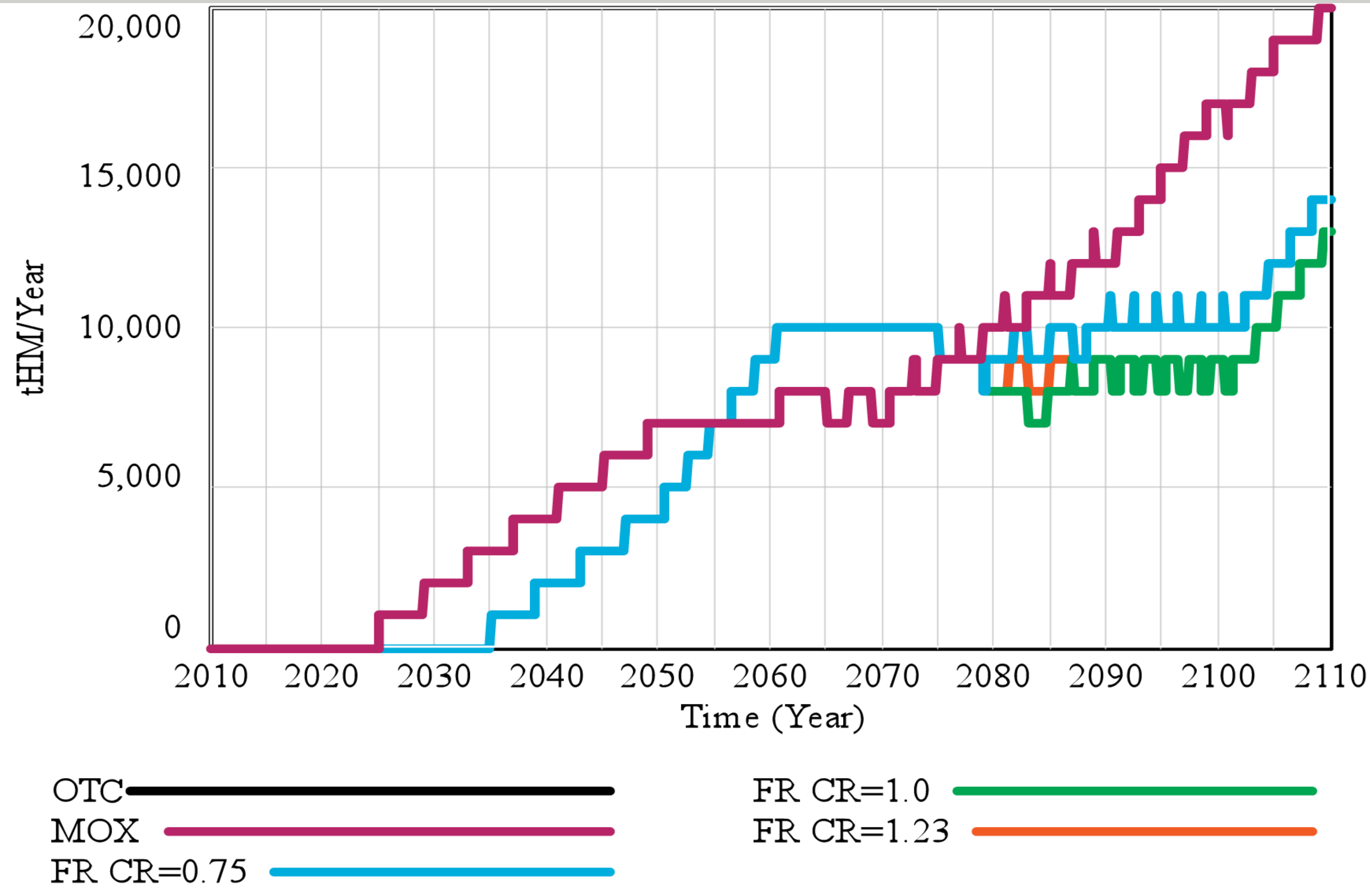
MOX has little effect, and fast reactors take decades to cause a real difference

Growth Rate	Fuel Cycle	By 2050	By 2100
1.0%	OTC	1.03	2.93
	MOX	0.88	2.34
	FR	0.98; 0.97; 0.98	1.77; 1.75; 1.77
2.5%	OTC	1.26	5.86
	MOX	1.11	4.86
	FR	1,21; 1.21; 1.21	4.16; 3.78; 3.76
4.0%	OTC	1.56	8.11
	MOX	1.41	6.77
	FR	1.51; 1.51; 1.51	5.80; 5.34; 5.34

Required LWR Spent Fuel Reprocessing Capacity

for the 2.5% Growth Case

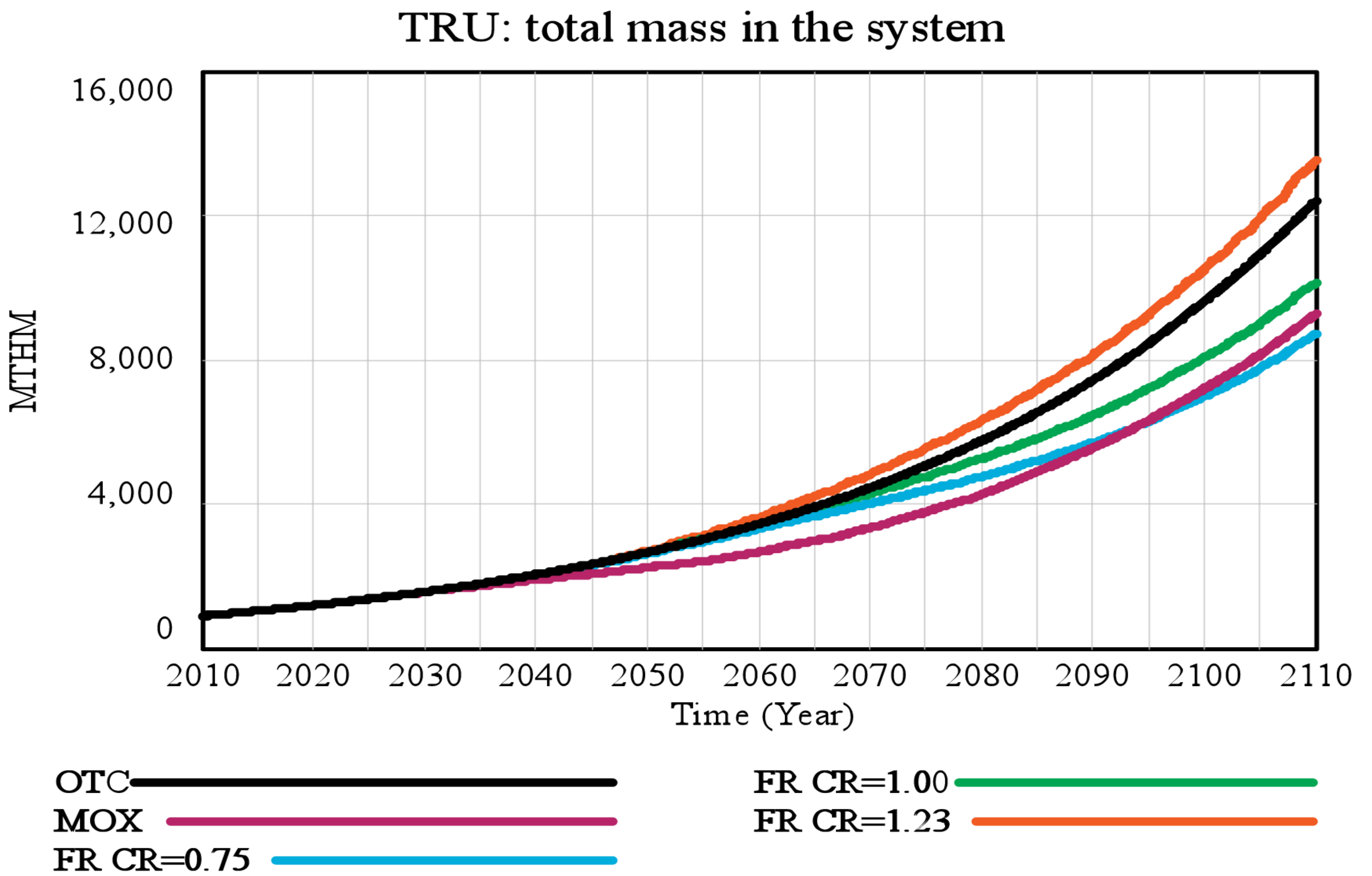
More capacity needed for lower conversion ratio reactors



Total TRU in system for 2.5% case

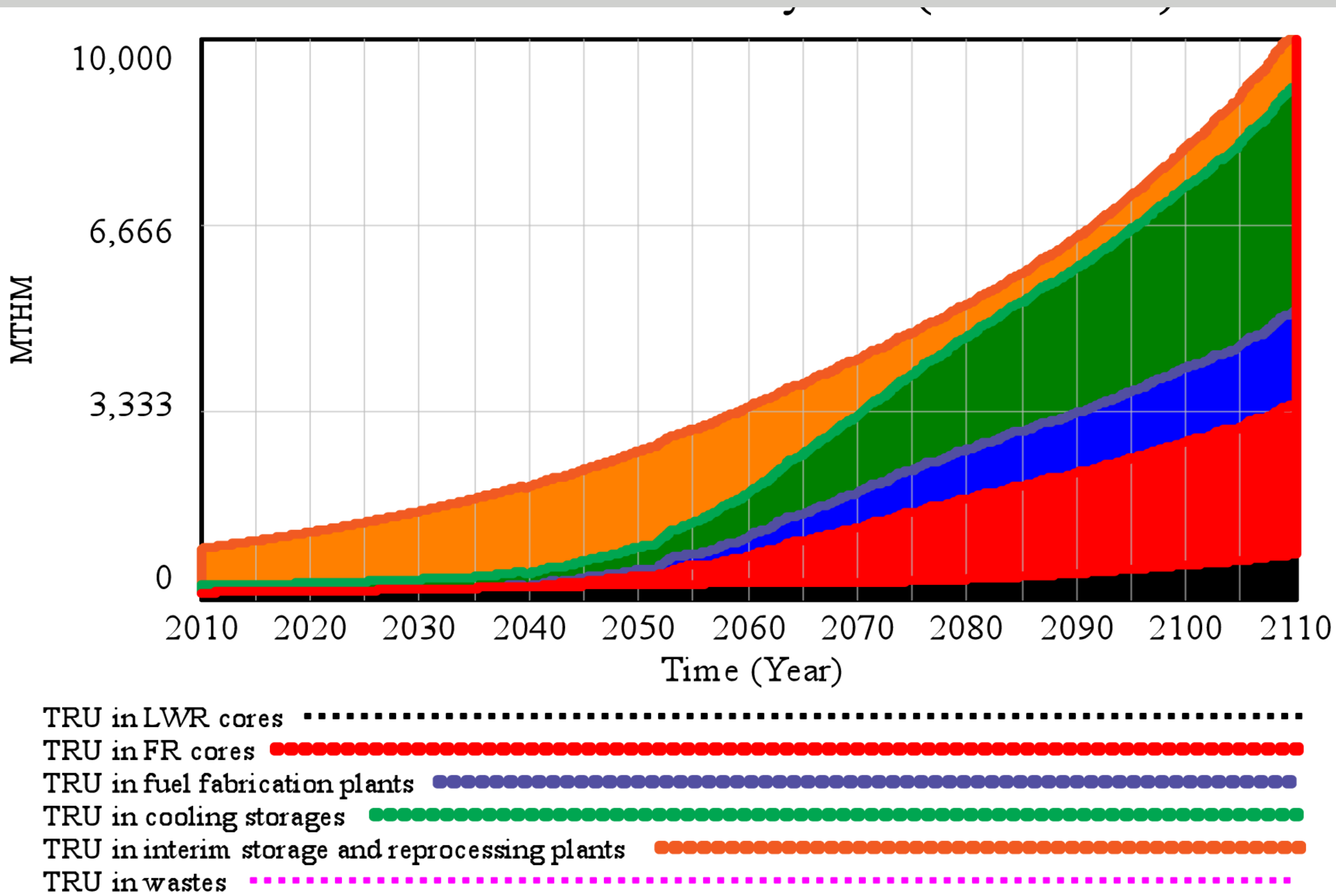
Recycling has a modest effect on total TRU in the system.

Total TRU = TRU In Reactors + Cooling and Interim Storage + Repository



Total TRU in the System

Most TRU is in cooling storage and in fast reactor cores

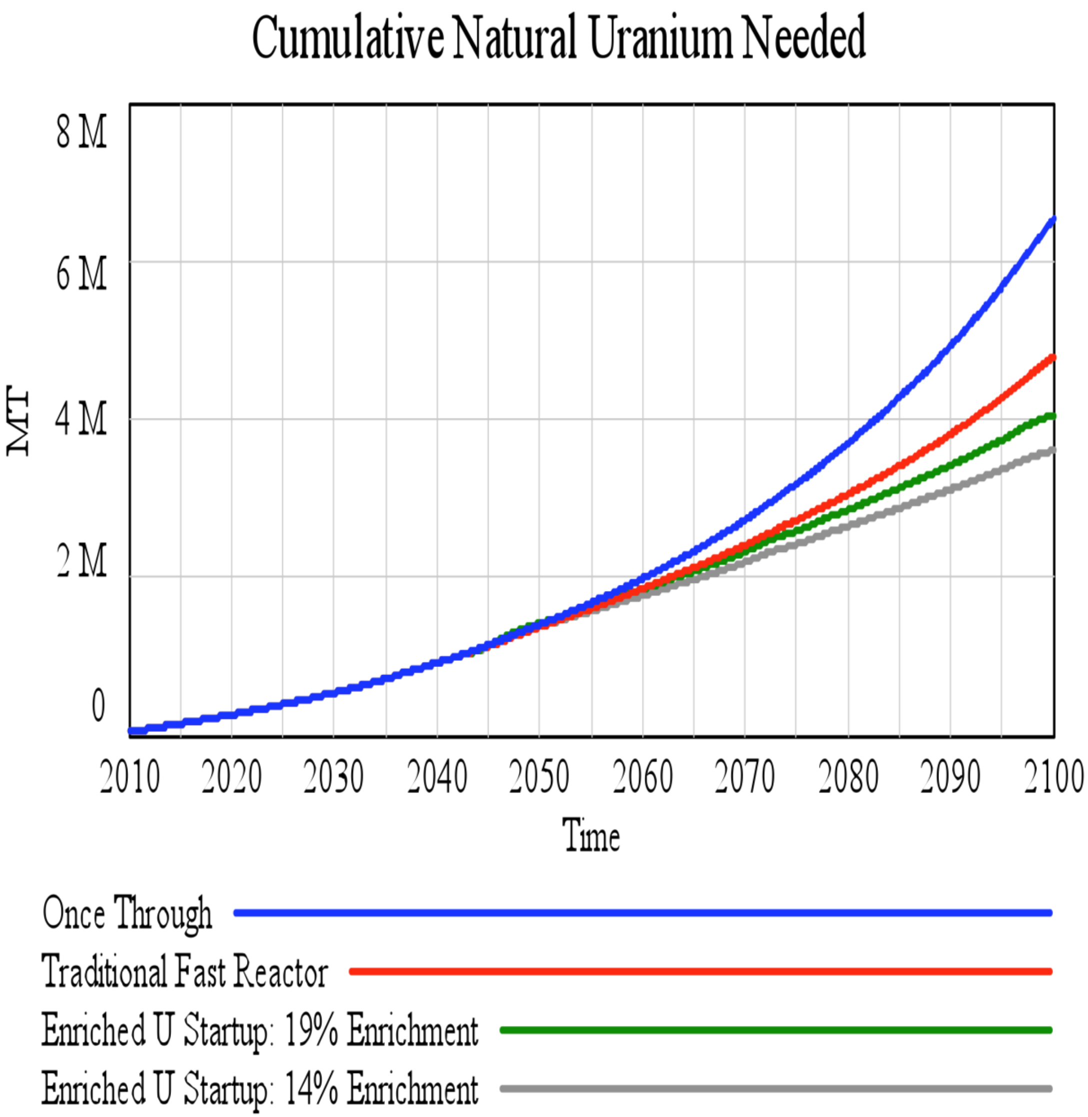


What if we start fast reactors with medium enrichment uranium rather than plutonium?

- 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 20%) startup of a self-sustaining reactor is possible when an effective reflector is used (like MgO).

Uranium Requirements for LWR and for FR Startup

For the base case of 2.5%



Allows more rapid fast reactor penetration.

Avoids recycling of LWR
spent fuel which has only
low fissile content.

Reduces overall SWU capacity needed.

Implications of cost of FR, and disposition of LWR spent fuel remain as open questions.

Conclusions – 1

- The controlling factors in the transition to advanced reactors with recycling:
  - Rate of demand growth
  - Availability of transuranics (TRU) from discharged fuels
  - A smaller role for industrial capacity for FR fuel recycle and manufacture
- LWRs will have a major role in nuclear energy in this century, even after introduction of advanced reactors.
- Recycling will have limited impact on natural uranium consumption in this century:
  - MOX 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 will lead to about 30% reduction.

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Conclusions – 2

- 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 in the short term.
  - A repository is still needed.
- Options to start fast reactors on Uranium exist, and may be advantageous to U consumption.
- Self-sustaining reactors, with conversion ratio of 1.0 offer advantages for transition to a closed system.
  - Choice of sodium reactors to maximize conversion ratio may not offer the optimum path forward.
  - Several options for fast spectrum reactors, e.g. water cooled hard spectrum reactors, may reduce the cost of a sustainable nuclear energy system.

Questions