The Future of the Nuclear Fuel Cycle

An Interdisciplinary MIT Study

Ernest J. Moniz
Cecil and Ida Green Professor of Physics and Engineering Systems
Director, MIT Energy Initiative

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Study Participants

Co-chairs: Mujid Kazimi and Ernest J. Moniz

Executive Director: Charles W. Forsberg

Steve Ansolabehere
John M. Deutch
Michael J. Driscoll
Michael W. Golay
Andrew C. Kadak
John E. Parsons
Monica Regalbuto

George Apostolakis
Pavel Hejzlar
Eugene Shwageraus

Blandine Antoine
Guillaume De Roo
Bo Feng
Laurent Guerin
Isaac Alexander Matthews
Lara Pierpoint
Behnam Taebi
Keith Yost

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James K. Asselstine, Barclays Capital
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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

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

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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?

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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

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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

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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 (incremental, cost-shared with industry)

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SNF Storage

Andrew Kadak

September 21, 2010

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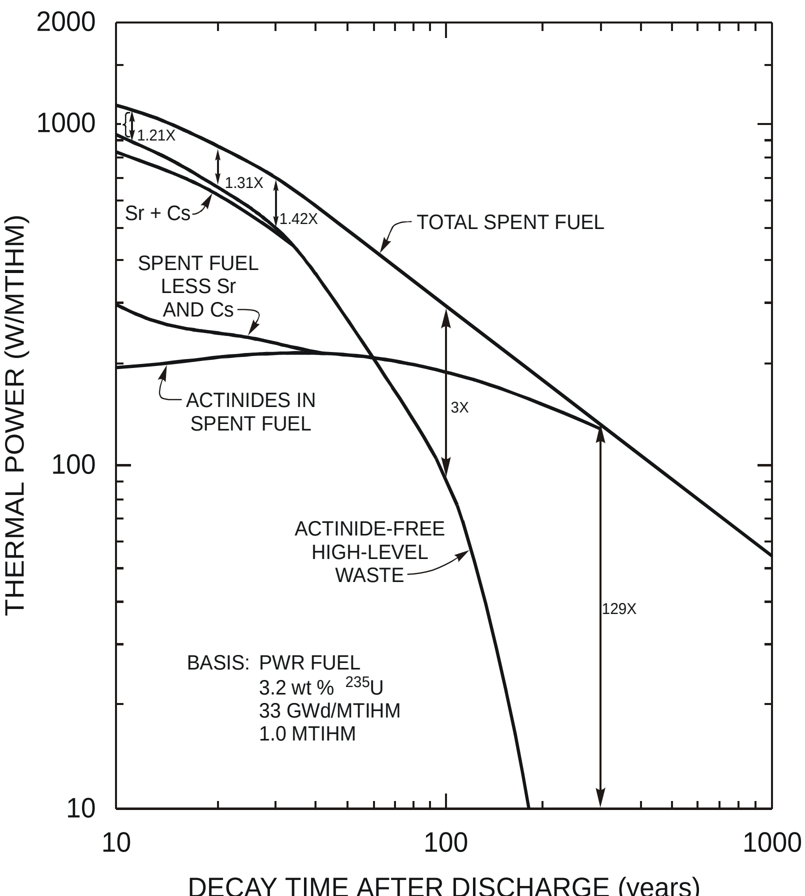
Repository Programs Store SNF to Reduce Repository Size, Cost, and Performance Uncertainties

- 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



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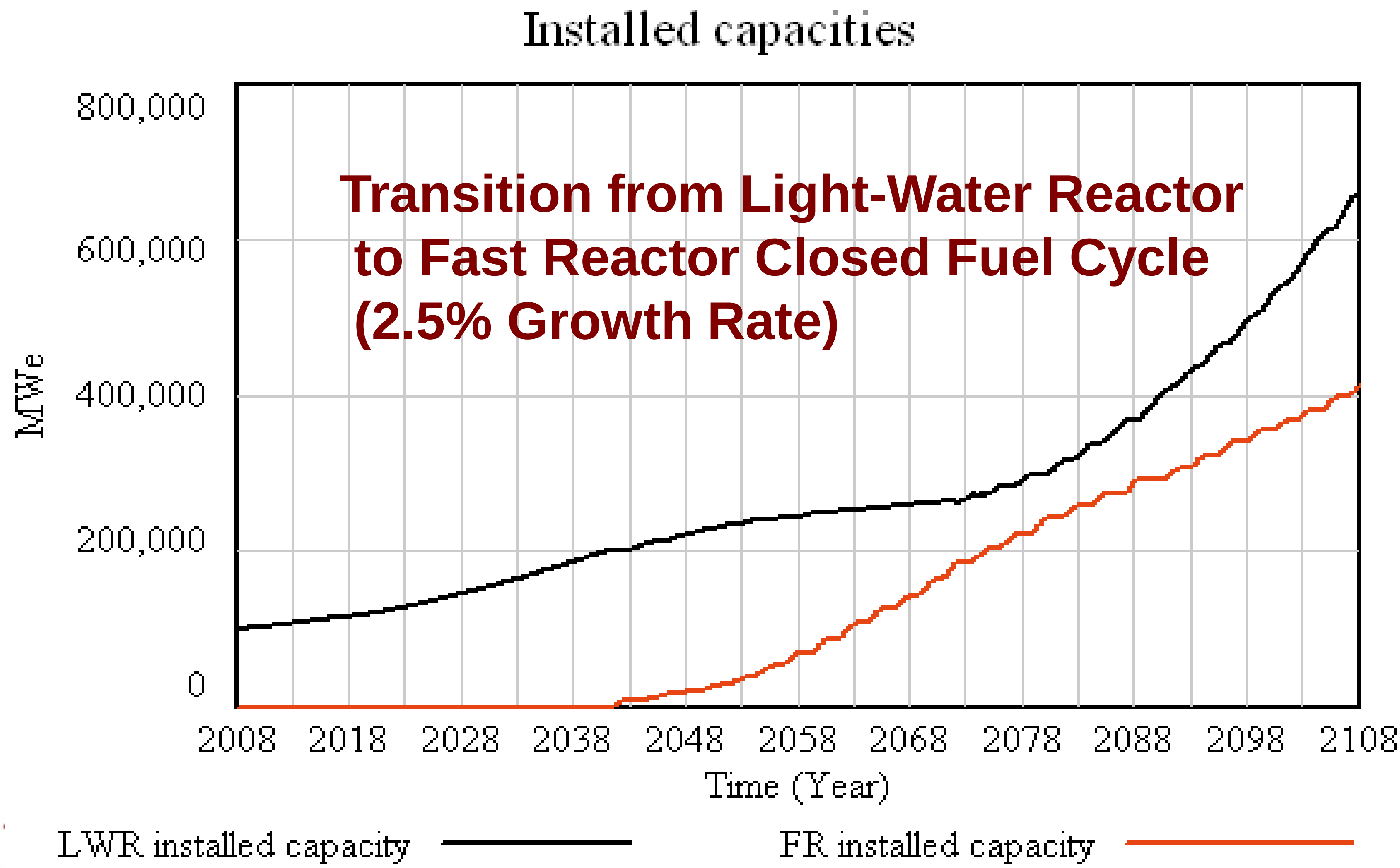
It Takes 50 to 100 Years for Fuel Cycle Transitions



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

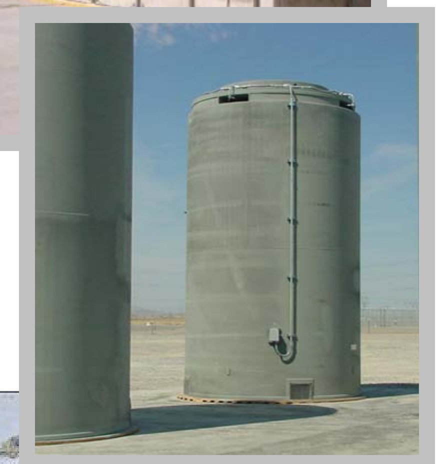
SNF Storage Options

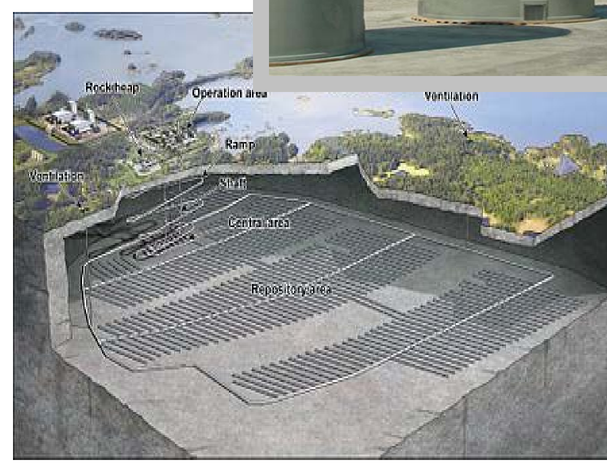
Finding:

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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Uranium and Fuel Cycle System Studies

Charles Forsberg

Executive Director MIT Nuclear Fuel Cycle Study

Massachusetts Institute of Technology
77 Massachusetts Ave; Bld. 42-207a; Cambridge, MA 02139
Tel: (617) 324-4010; Email: cforsber@mit.edu

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MIT Center for Advanced Nuclear Energy Systems

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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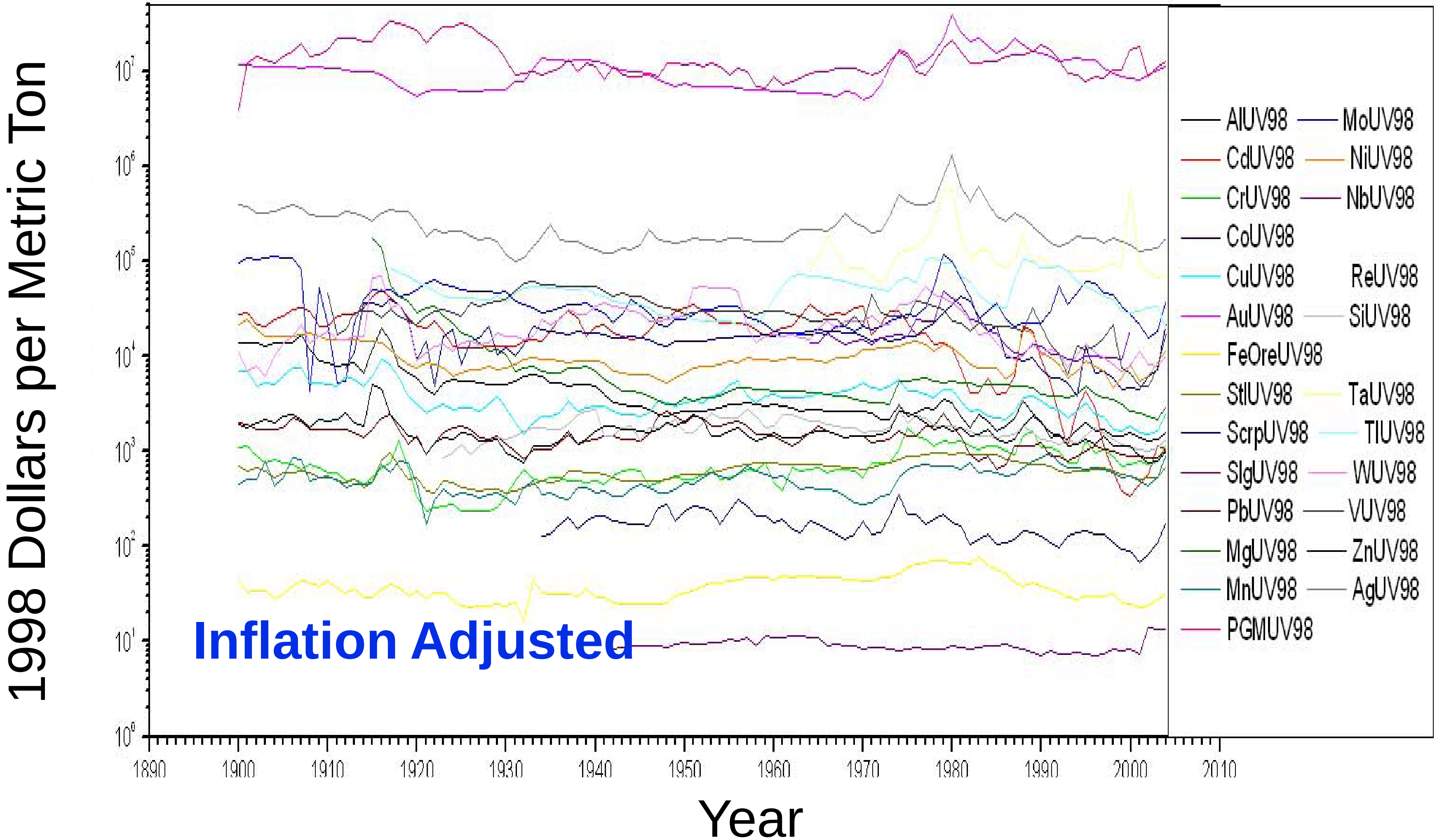
Uranium Cost Assessment

- Uranium is 2 to 4% of the cost of nuclear electricity
- 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: 50% increase in uranium cost (1 to 2% increase in electricity costs) 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



Dynamic Simulation of the Nuclear Energy System

Objective:

Examine implications of a reasonable range of nuclear energy assumptions and 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?

Modeled Multiple Fuel Cycles Over a Century

Three nuclear growth rates: 1, 2.5, and 4% per year

Three fuel cycle options:

- Light-water reactor once-through fuel cycle
- Light-water reactor with recycle of LWR SNF
- Light-water reactor SNF TRU to fast reactors

Fast reactors with three conversion rates (rate of fissile fuel production versus consumption)

- CR = 0.75 (Actinide burner)
- CR = 1.0 (Make fuel as fast as consume fuel)
- CR = 1.23* (Make fuel faster than consume fuel)

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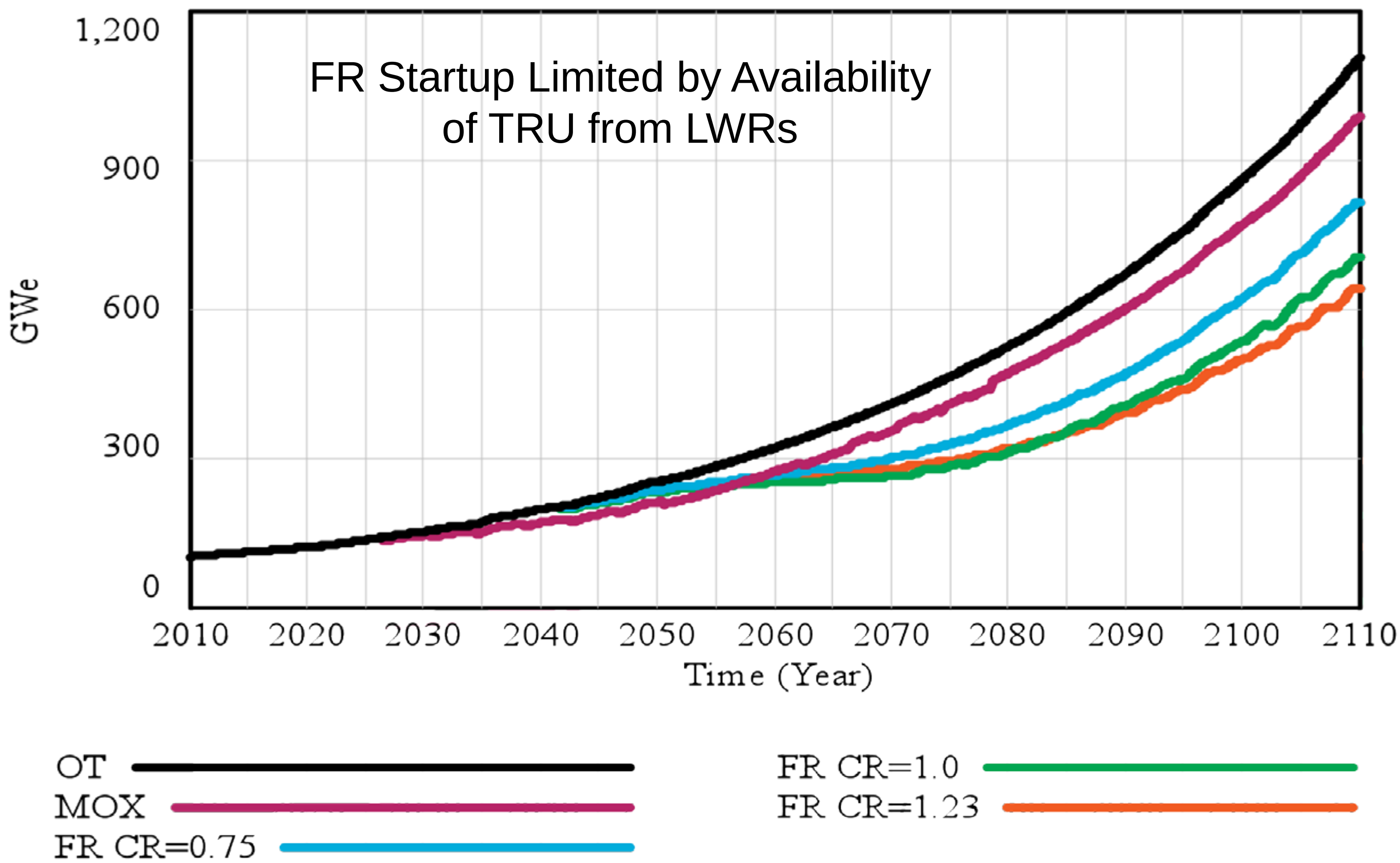
*Traditional future vision of closed fuel cycle using 1970s assumptions

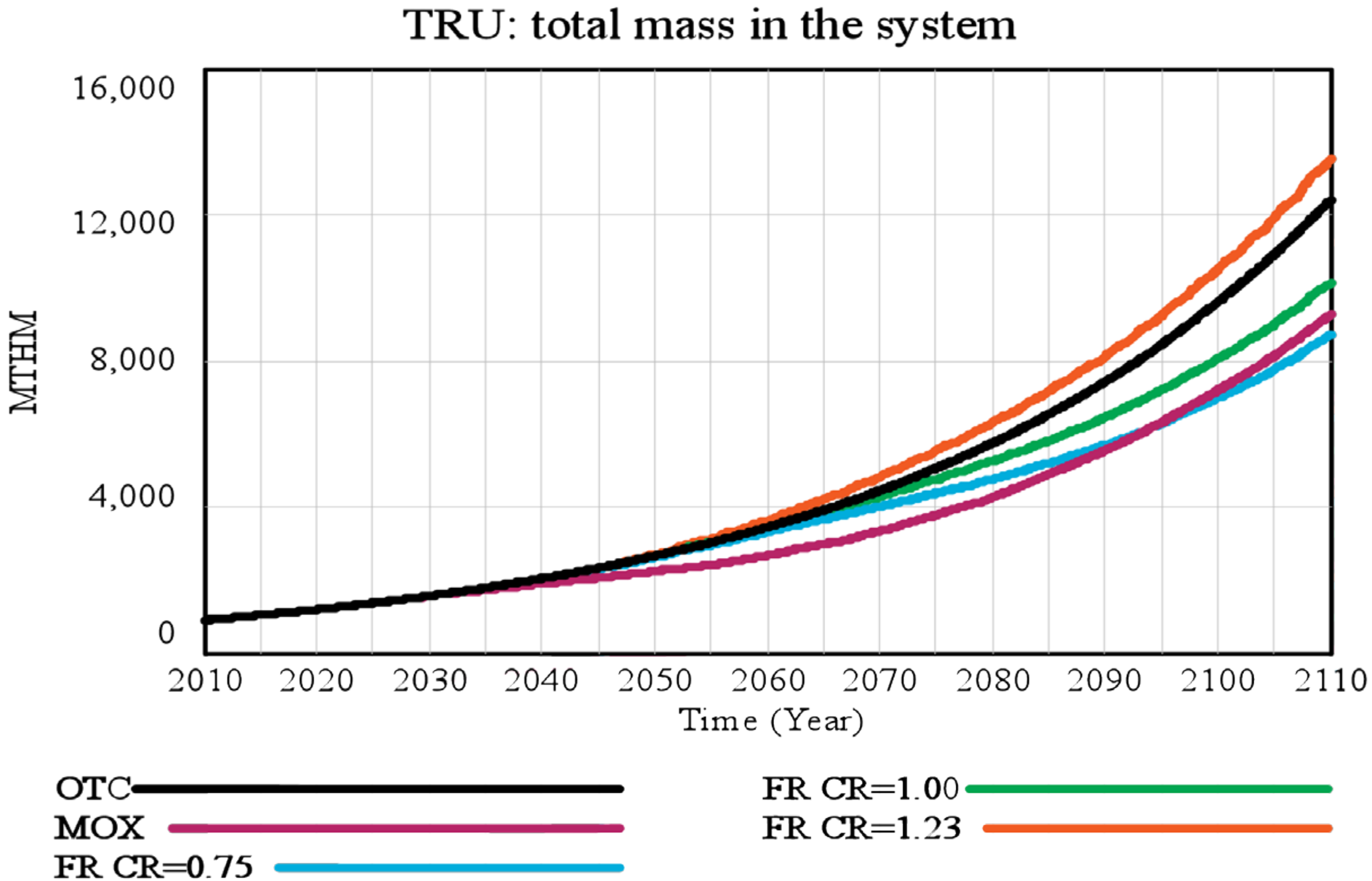
Installed LWR Capacity on UO_2 Fuel (2.5% Growth Case)



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



Cumulative Demand for Uranium (1M MT)

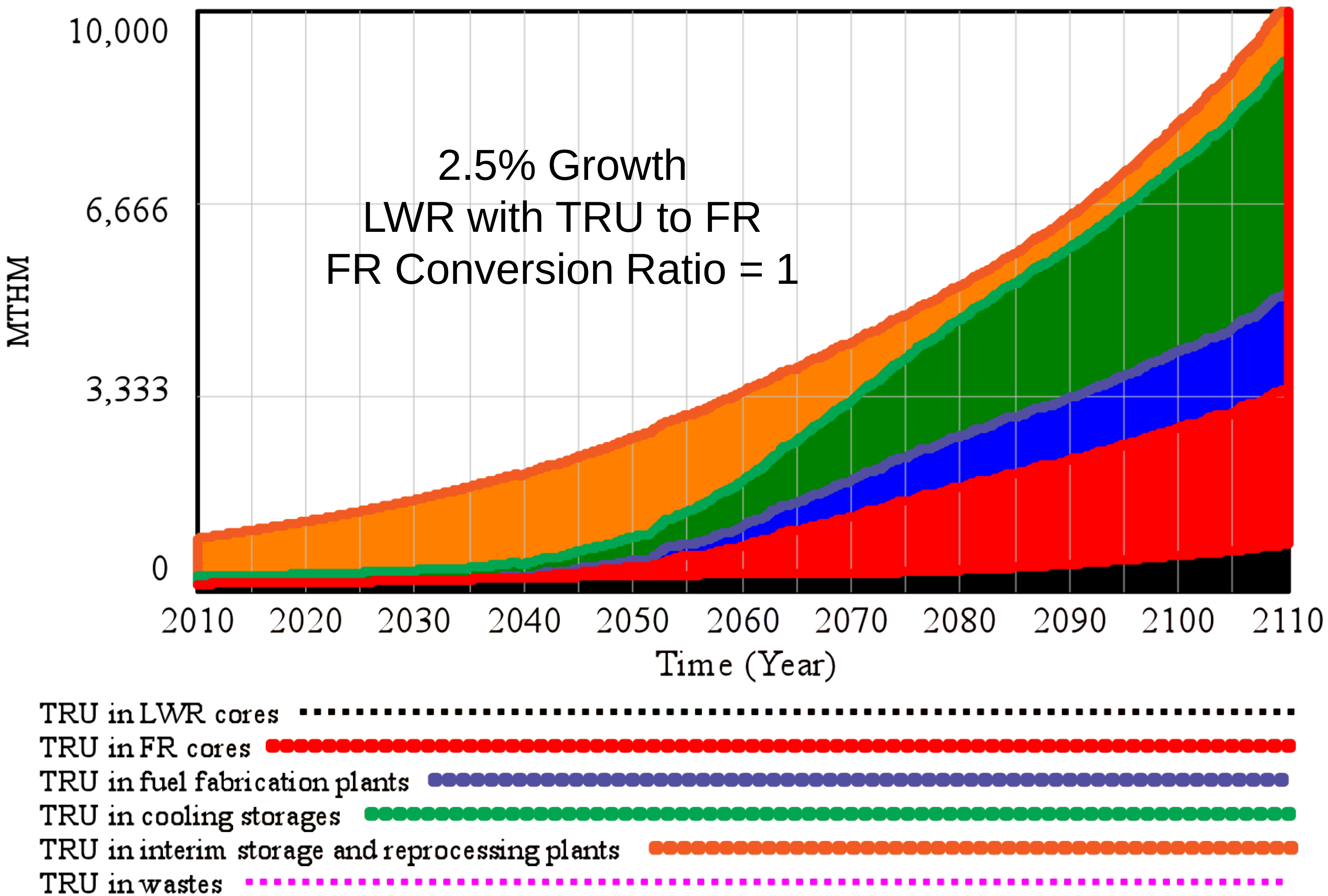
MOX has little effect, and fast reactors take decades to cause a real difference

Fuel Cycle	By 2050	By 2100
Once-Through LWR	1.26	5.86
MOX LWR	1.11	4.86
LWR-Fast Reactor: CR = 0.75	1.21	4.16
LWR-Fast Reactor CR = 1.0	1.21	3.78
LWR-Fast Reactor CR = 1.23	1.21	3.76

2.5 % Growth Rate

Location of TRU in LWR-FR System

Most TRU is in cooling storage and in fast reactor cores



Conclusions for Growth Scenarios

- Transition times between fuel cycles are 50 to 100 years
- LWRs will have a major role in nuclear energy in this century
- Recycling has limited impacts on natural uranium consumption in this century
- Recycling does not lead to appreciable reduction of TRU in total energy system in this century, but leads to significant reduction in the amount of TRU destined to the repository in the short term
- There is little difference in outcomes with a fast reactor with a conversion ratio of 1 versus 1.23

Implications from Dynamic Systems Analysis and Advancing Technologies

- Lowering CR to 1 (from the historical CR>1.2) and new technologies opens up multiple sustainable reactor options
  - Sodium fast reactor (Historical base case)
    - Chosen in the 1970s based on uranium resource understandings, limited capability to model CR implications, and available technologies
  - Hard-spectrum LWR
  - Lead-cooled fast reactor
  - Salt-cooled high-temperature reactor
- Some of these new options may have superior economics and other characteristics
- CR ~1 and new technologies may enable startup of fast reactors on low-enriched uranium

What if we start fast reactors with low enriched uranium (<20% ^{235}U) 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 low enriched uranium (under 20%) startup of a self-sustaining reactor is possible when an effective reflector is used (like MgO).
- Decouple LWR and FR fuel cycles

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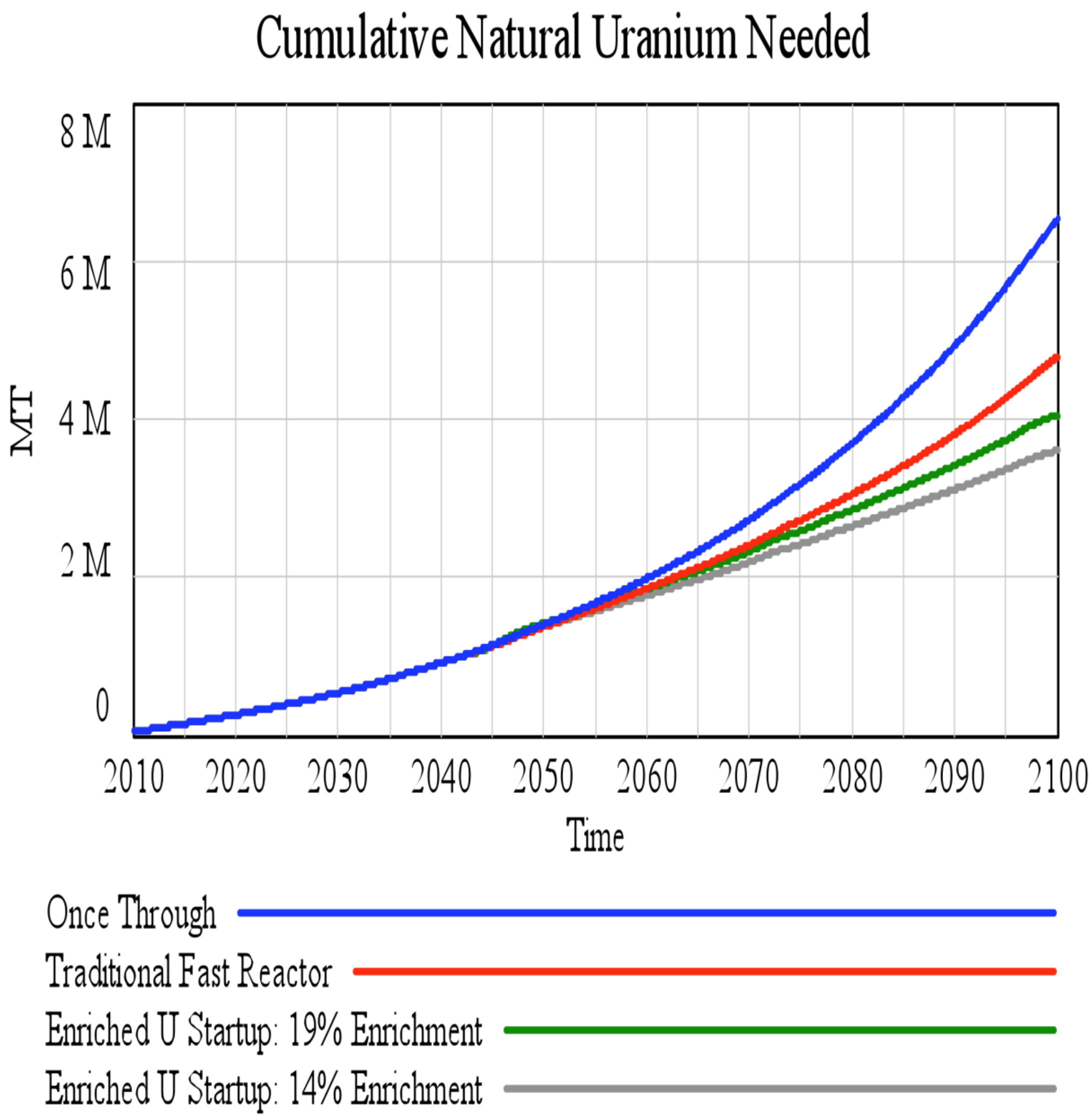
Uranium Requirements for LWR and FR Startup

For the base case of 2.5%; CR = 1



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.

Fuel Cycle Recommendation

Integrated systems studies and experiments on innovative reactor and fuel cycle options should be undertaken in the next several years to determine the viable technical options, define timelines of when decisions need to be made, and select a limited set of options as the basis of the path forward

Questions