Nuclear Fuel Cycles: Differences and Similarties

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Attributes of a Desirable Fuel Cycle

- Economic. Here the emphasis is on what is the cost of the associated technology, since that cost is currently about 70% of the cost of nuclear electricity.

- Has Vast Fuel Resource. Maximizing the utilization of the energy potential from nuclear fuel is a benefit for mankind as it provides many future generations of an option for their needed energy.

- Minimizes the burden of waste products. Thus the handling of waste products in the short and long term would pose negligible risk to the public and the environment.

- Maximizes the proliferation resistance associated with its operations. Thus, the fuel should be undesirable as a potential weapons material at any of the stages involved. The treatment of the fuel to make it a desirable weapons material should be complex and costly.

Why economics can improve

- The most economic nuclear fuel cycle is the once-through use of mined uranium in LWRs, as long as uranium supplies remain inexpensive.
  - The predominant choice of all countries demonstrates this attribute.
  - Shares technology development costs with fossil power plants (pumps, valves, turbines, etc)
  - Has a relatively wide industrial base, so it does not require starting from scratch
  - Benefit from lessons learned from construction and operation of over 300 plants all over the world.

- Steps that might further reduce the cost of the plants per KWe:
  - Standardization: Exemplified by France and Korea, may provide 20% reduction
  - Power Uprates: New designs of fuel, new operating conditions and new coolant technology (nanofluids) should help reduce the cost by 20%
  - New construction techniques may reduce by 10%
  - New licensing process, may reduce by 10%
  - Elimination of the financing risk premium (support for first movers, and development of medium size reactors (500 to 1000MWe).

Fuel Cycle Basics

- 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.

- For the same nuclear energy output, all fuel cycles produce roughly the same fission products, thus, roughly equal burden for heat removal from used fuel in storage for the first 200 years. Advanced fuel cycles with recycling can dramatically reduce the transuranic loading (i.e. long term heat load) of a repository, not the fission product burden.

- 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.

Choices: Reactors and Recycling

1 GWe 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
- *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
- Multirecycling in thermal spectrum LWRs is more challenging than in fast reactors due to buildup of spontaneous neutron sources and non-fissile Pu and MAs

1 GWe Fast Reactor with Recycle

- Initial core requires 7 to 10 MT TRU plus about 50 MT U
- *35 -50 years of operation of 1 LWR to start 1 FR*
- Large commercial reprocessing plant 800MT/yr: nearly 1 year of operation per one initial FR core
- Alternative startup on enriched uranium (at <15% enrichment) is possible for reactors that have a conversion ratio of 1.0
- A full FR core with unity conversion ratio produces yields fuel for one FR fresh core. More for breeders (since CR>1).

Modeled Multiple Fuel Cycles Over a Century

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

Three fuel cycle options:

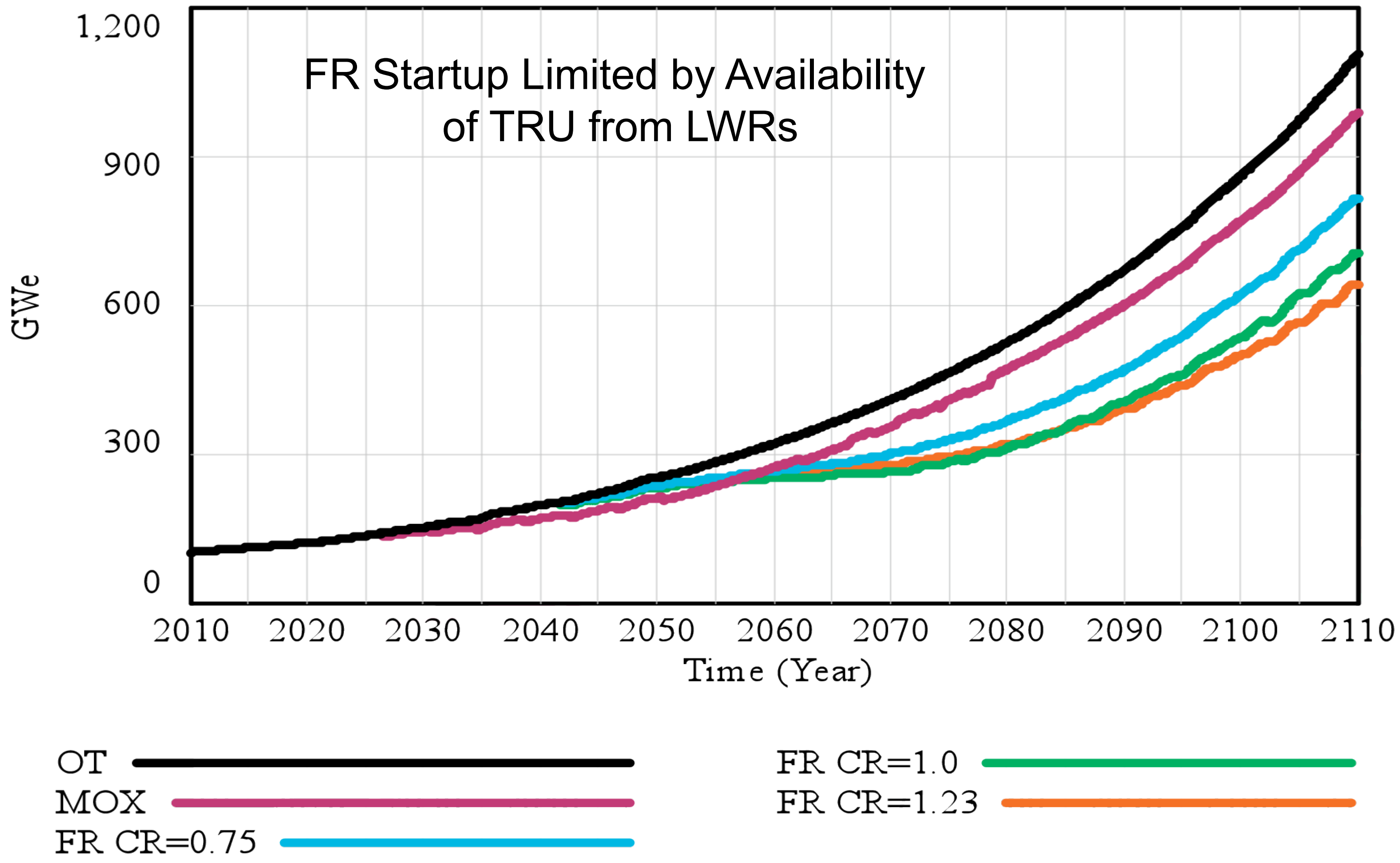
- Light-water reactor once-through fuel cycle
- Light-water reactor with recycle of LWR SNF
- Light-water reactor SNF TRU to fast reactors

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)

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

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



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

Cumulative Demand for Uranium (1000 MT)

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

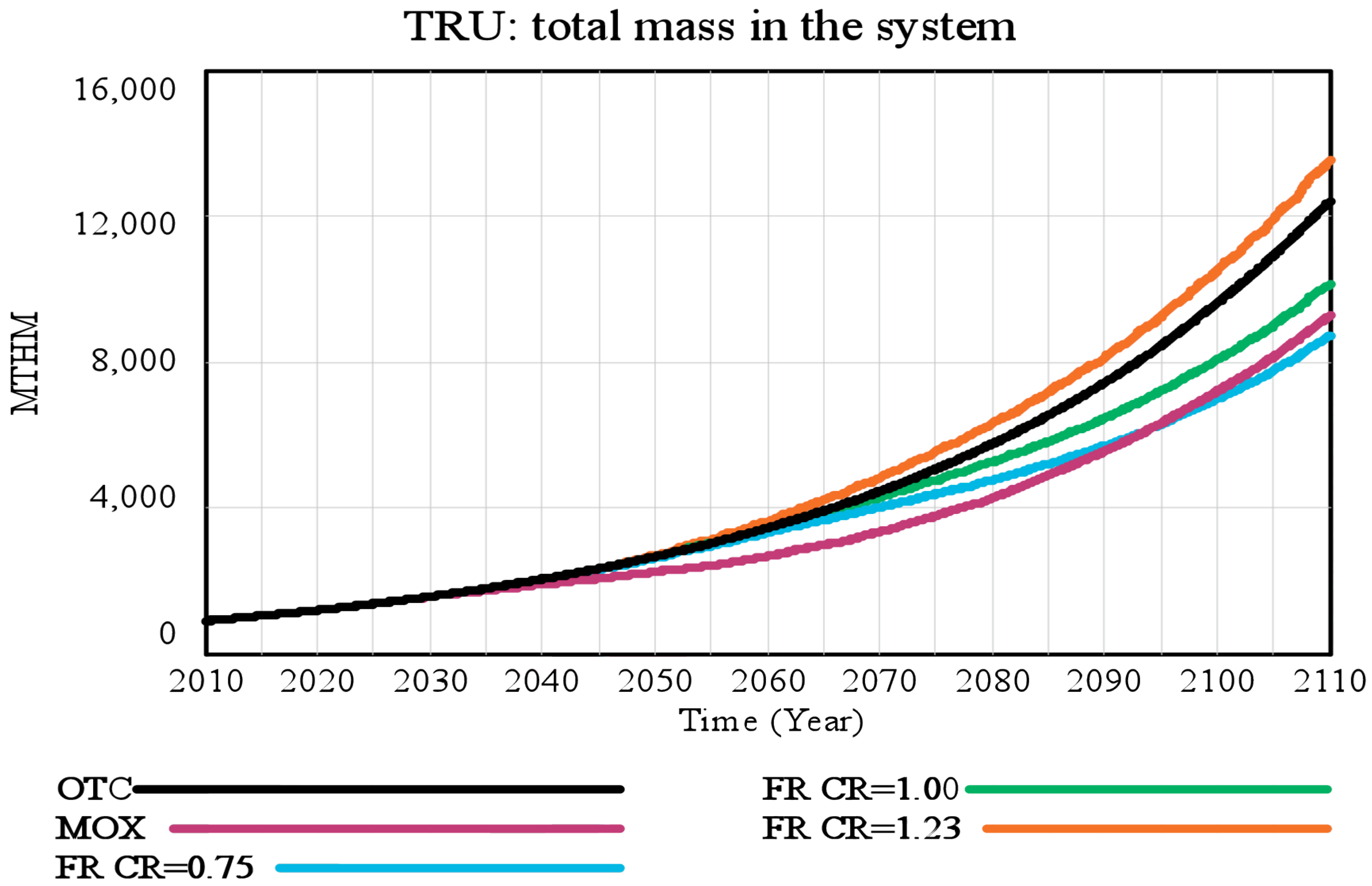
Growth Rate	Fuel Cycle	By 2050	By 2100
1.0%	OTC	1,105	3,064
	MOX	961	2,516
	FR*	1,058	1,970
2.5%	OTC	1,382	6,299
	MOX	1,226	5,361
	FR*	1,311	4,060
4.0%	OTC	1,749	8,591
	MOX	1,593	7,295
	FR*	1,679	5,831

* For Conversion ratio =1.0

Total TRU in system for 2.5% case

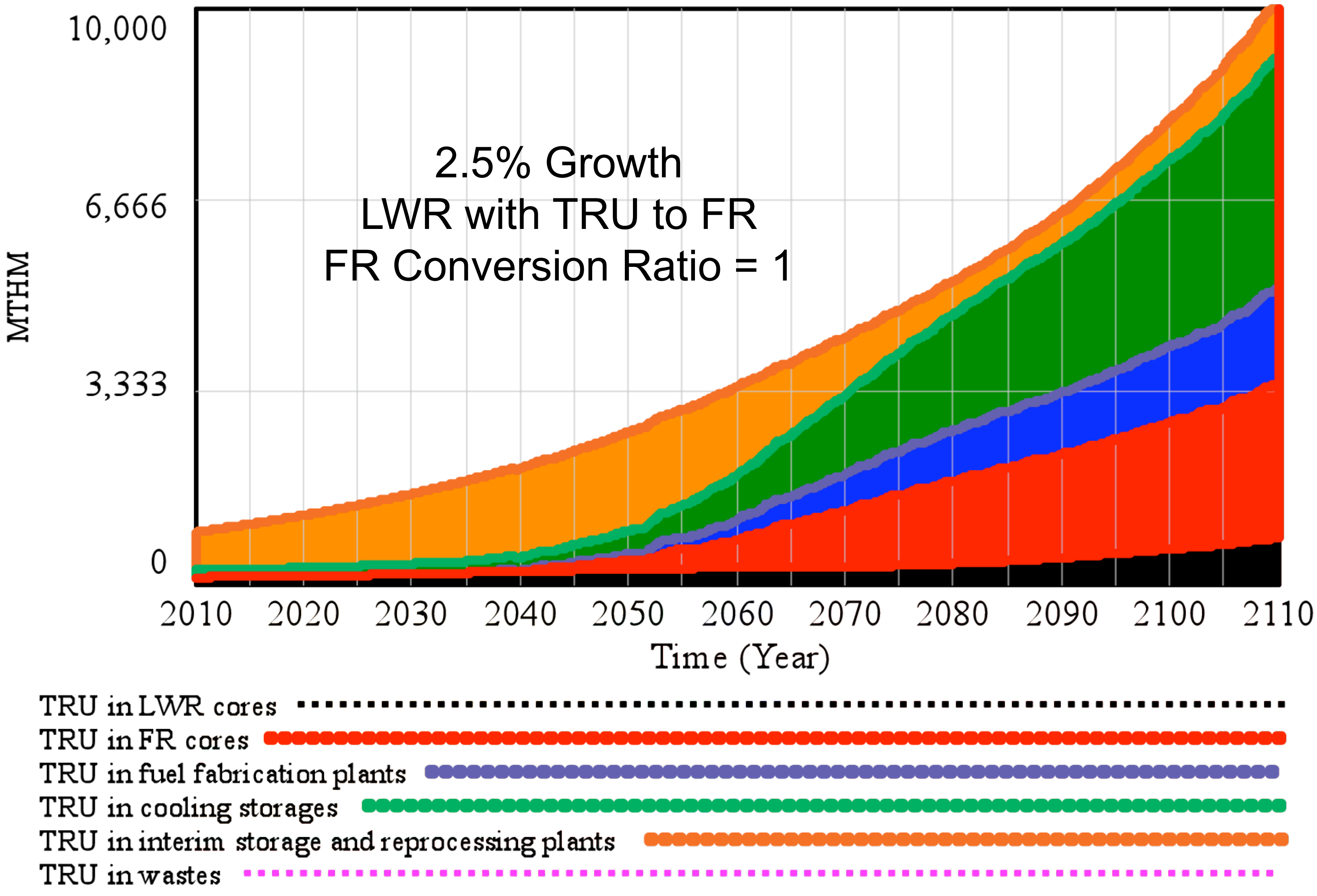
Recycling has a modest effect on total TRU in the system.

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



Location of TRU in LWR-FR System

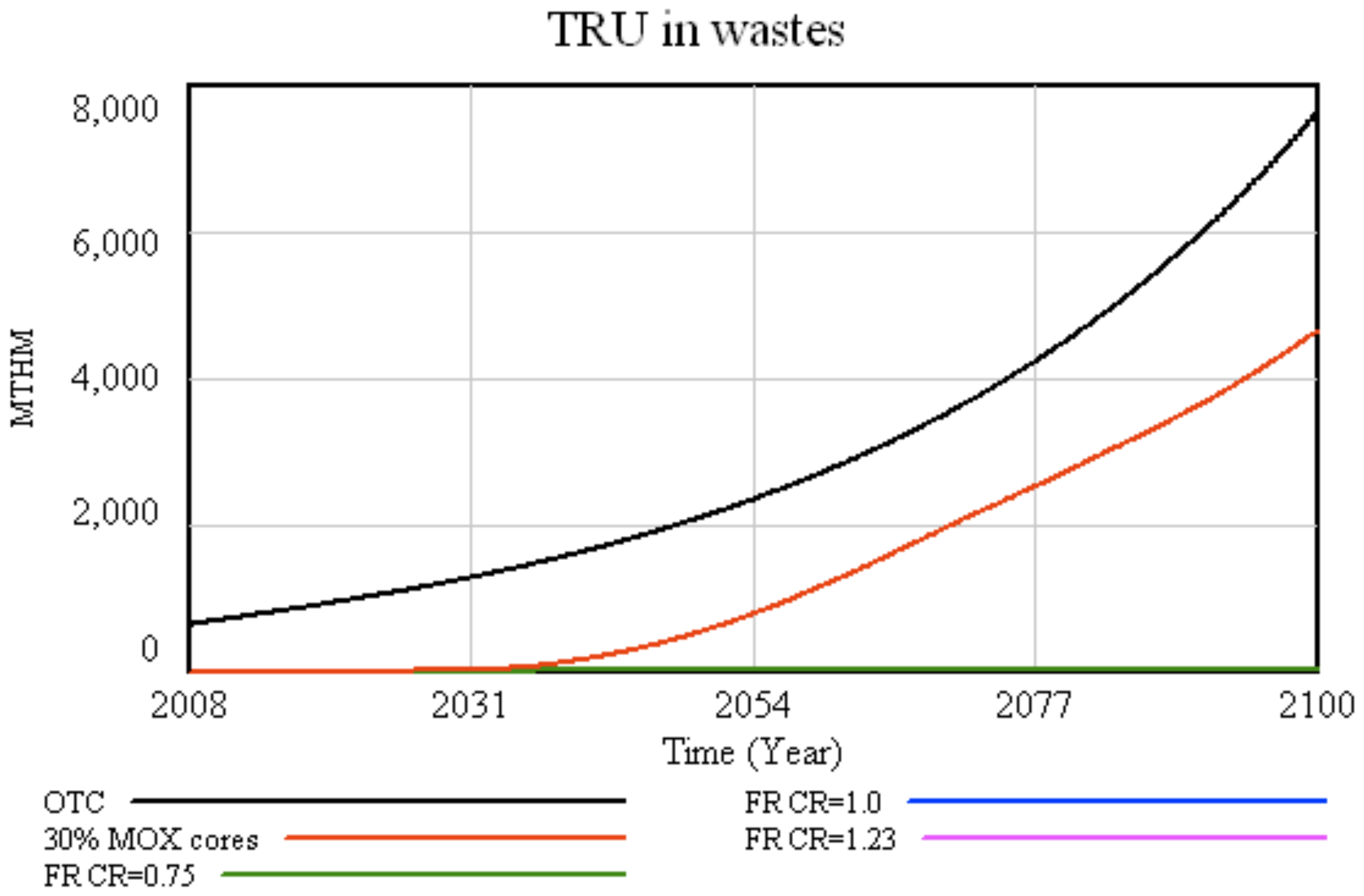
Most TRU is in cooling storage and in fast reactor cores



2.5% Growth
LWR with TRU to FR
FR Conversion Ratio = 1

TRU in wastes for 2.5% case

Significant reduction of TRU to repository is possible via recycling



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 impact 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 For Future Technologies

- Lowering CR to 1 (from the historical CR>1.2) 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
  - Gas-cooled fast reactor
  - Salt-cooled high-temperature reactor
- Some of these new options may have superior economics and other characteristics
- The fuel cycle with CR=1 reactors will minimize the needed recycling technology capacity.
- CR ~1 may enable startup of fast reactors on low-enriched uranium