Modeling Deployment Scenarios For A Fast MSR Fleet

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Introduction

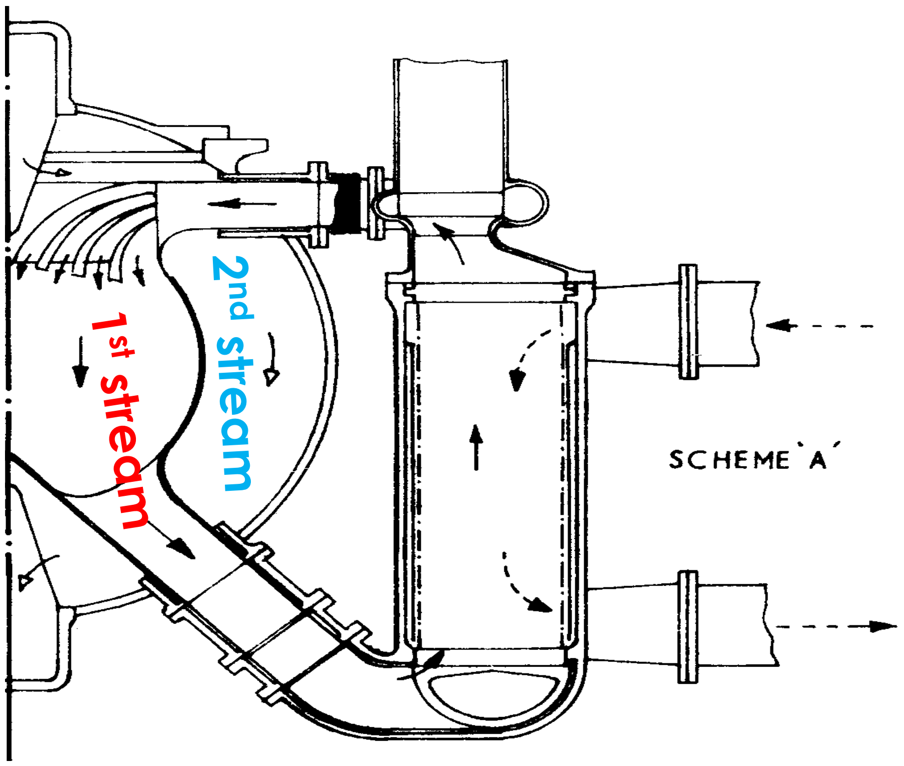
- This talk will focus on analyzing a fast MSR (FMSR) model in ORION to understand the current capability of modeling MSRs with this tool
  - Work done within the Systems Analysis and Integration Campaign (formerly the Fuel Cycle Options Campaign)
- Set up a single FMSR model to verify that results generated by ORION are in good agreement with SCALE reactor physics model
- Set up a *transition fuel cycle model* representative of the current fleet of LWRs in the US and provided a retirement profile
  - **Goal:** Study material availability in successfully deploying FMSRs to replace current LWR fleet

Outline

- Reactor physics model
- What is fuel cycle assessment?
- ORION: systems dynamics fuel cycles code
- Single FMSR ORION model
- Transition model
- Key conclusions

FMSR Reactor Physics Model

- Based on a modified design of molten chloride fast breeder reactor utilizing a U/Pu fuel cycle
- Two-stream system
  - First stream ($PuCl_3$-NaCl fuel salt) circulates within the core
  - Second stream (UCl_3-NaCl coolant salt) in annular blanket surrounding the core region
  - FMSR analyzed here is a single-fluid design that combines these two salts (similar to expected modern chloride MSR designs)



½-core fast spectrum design.[1]

[1] "An Assessment of a 2500MWe Molten Chloride Salt Fast Reactor" (1974).

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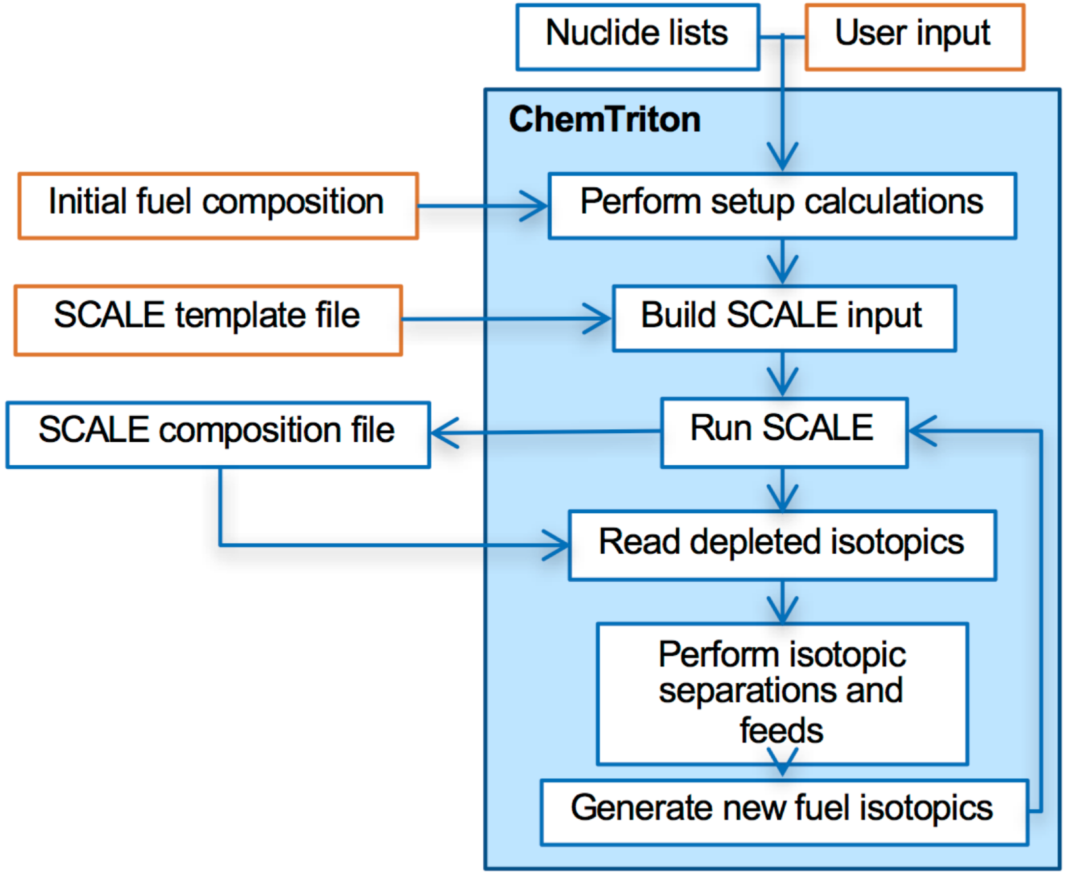
FMSR Reactor Physics Model

- ChemTriton used to model FMSR with SCALE
  - Models salt treatment, separations, discards and fueling using single- or multi-zone unit cell models
- Simulations for FMSR used a single representative zone 2D unit cell model
- No structural components were represented in these models to simplify analysis
- Used 3-day depletion time steps
  - Salt treatment and processing cycle times are set to 3 days for all fission products in order to remove them at each time step

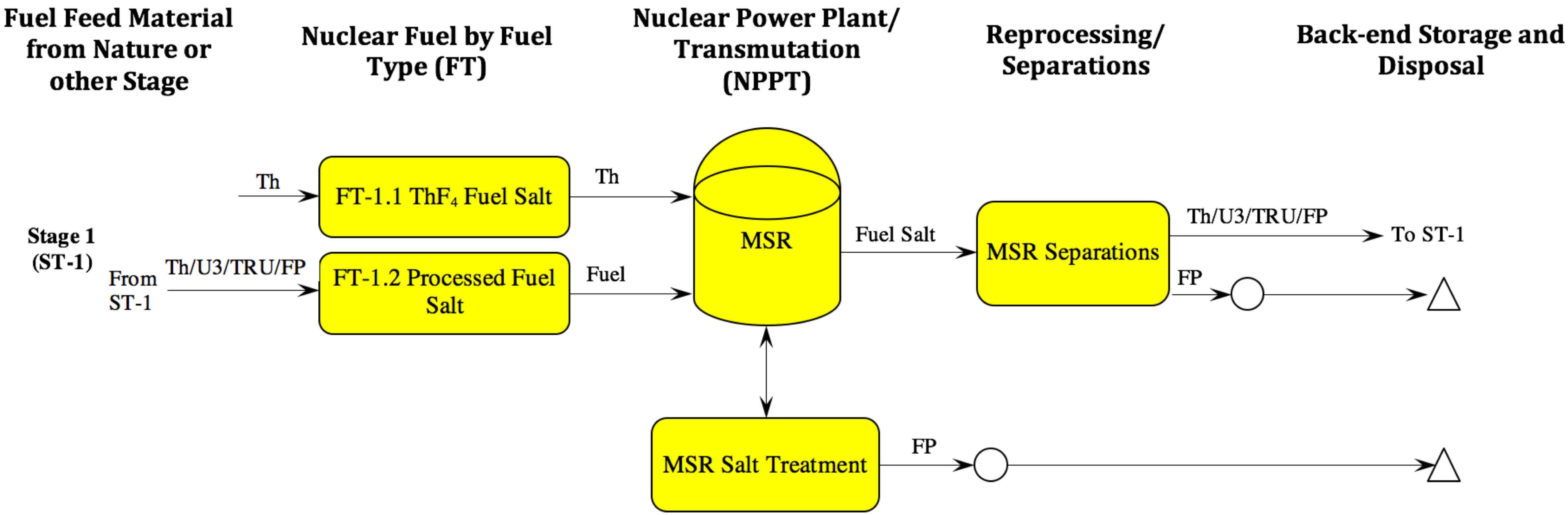


B. R. Betzler, J. J. Powers, and A. Worrall, “Molten Salt Reactor and Fuel Cycle Modeling and Simulation with SCALE,” Annals of Nuclear Energy, 101, pp. 489–503 (2017).

Reactor Physics Analysis

Integrates more tightly with fuel cycle analysis

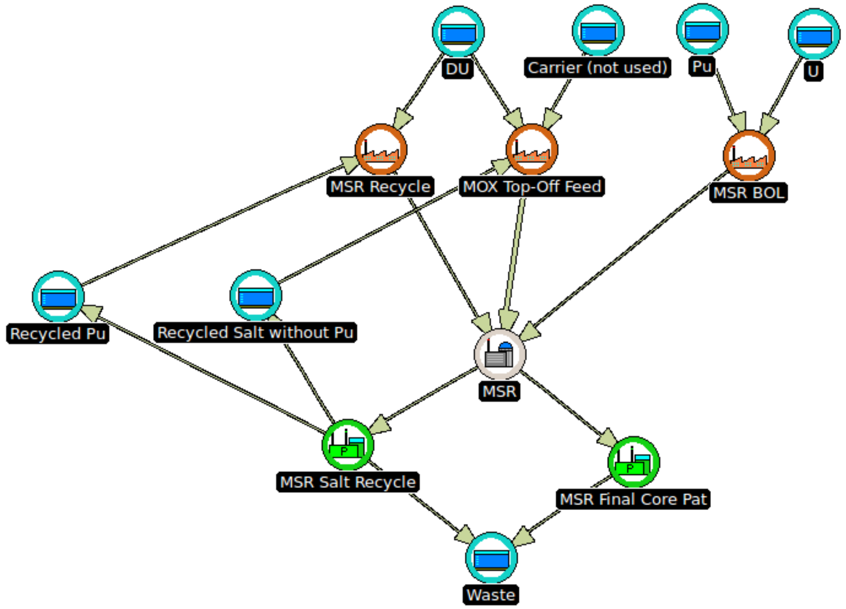
- Reactor physics performance of a molten salt reactor is not well understood without simulating material additions and removals



Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors

Fuel Cycle Assessment

- Assessing a given fuel cycle over ***time*** (historic, current and future), requires analysis of:
    1. Transformation of materials
    2. Flow of materials within the fuel cycle
    3. Economics
- ORNL uses ORION, a systems dynamics fuel cycles code developed and maintained by the National Nuclear Laboratory (NNL) in the UK



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ORION

- Can simulate storage facilities, fabrication and enrichment plants, reprocessing facilities, and reactors
  - GUI front end
  - Tracks >2500 nuclides
  - Models decay and in-reactor irradiation
  - Can use:
    - Recipes (pre-calculated isotopic fractions of spent fuel)
    - Burnup-dependent cross section libraries
    - Inline SCALE/ORIGEN coupled calculations
  - Automatic deployment of reactors based on fissile material in storage, growth rate of nuclear energy, and commissioning/decommissioning profiles

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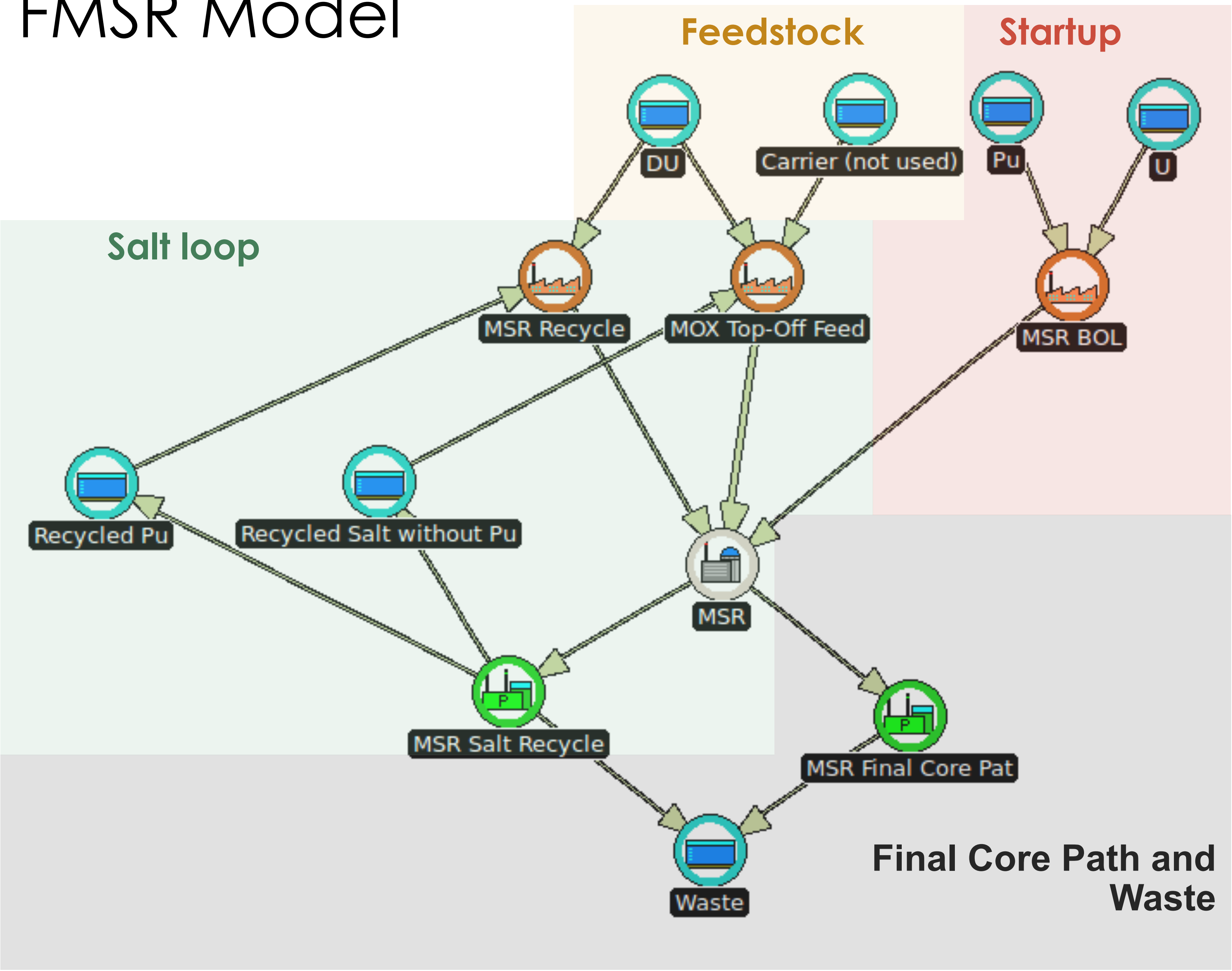
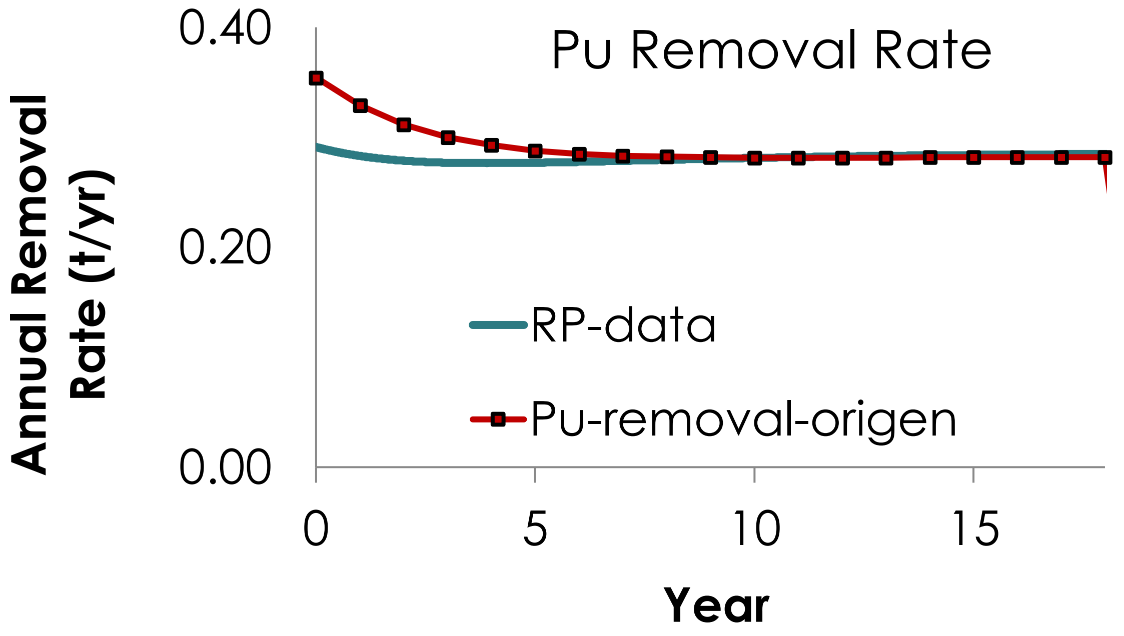
First Step: Create single FMSR model in ORION

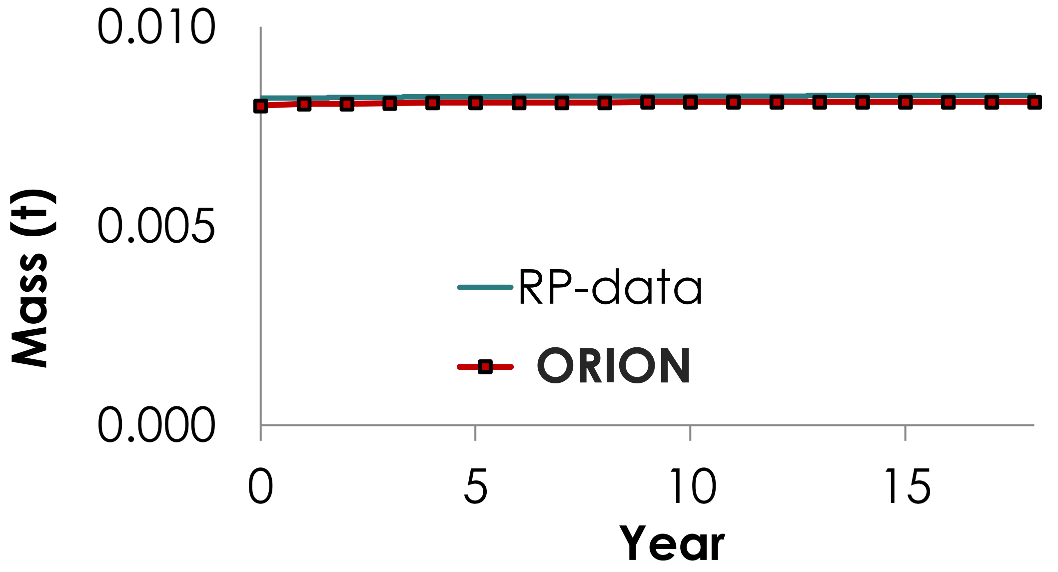
Single FMSR Model



ChemTriton vs. ORION

- ChemTriton results for unit cell compared to ORION results
- Results show good agreement
- Stable and longer lived isotopes easier to compare
- ^{148}Nd removal in excellent agreement
  - Burnup is accurately predicted by ORION/ORIGEN coupled results





Second Step: Set up fuel cycle model to evaluate FMSR deployment

Deployment Analysis

- How do you analyze deployment of FMSRs?
  - Set up a model that is representative of our current fleet of LWRs
  - Set up FMSR model
  - Provide retirement profile of LWR fleet
    - Based on this retirement profile and material availability, ORION's Dynamic Reactor Control tool will deploy fast MSRs
- Transition analysis (LWR → FMSR fleet) was performed to study the trends and performance of the FMSR deployment
- We know:
  - MSRs have low excess reactivity and continuous refueling increases the overall resource utilization
  - MSR fuel can achieve an almost zero out of core time when compared with an SFR where delays due to cooling, reprocessing and fuel fabrication are required
  - How does this affect transition?

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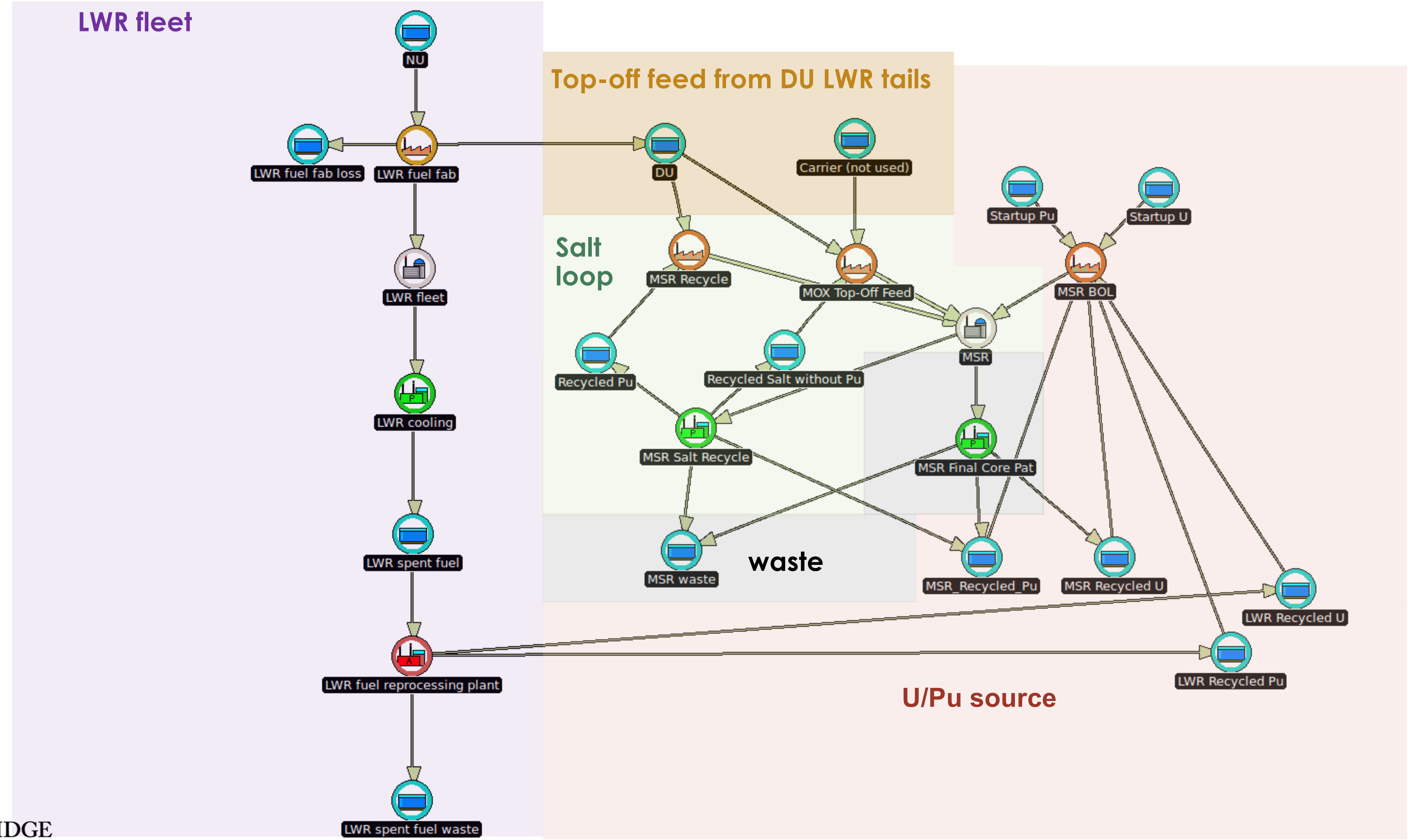
Deployment Assumptions

- **Objective: Replace electric capacity of existing LWR fleet (1000 MWe) with FMSR fleet**
- LWR simulation begins in 2015
- LWRs retire from 2050 to 2070 (assumes 80 year lifetime for LWRs)
- Reprocessed LWR spent fuel (after 2015) is available for use in new FMSR
- Assumptions consistent with SFR deployment scenarios analyzed within the Fuel Cycles Options Campaign

Transition from current LWR fleet to future FMSR fleet



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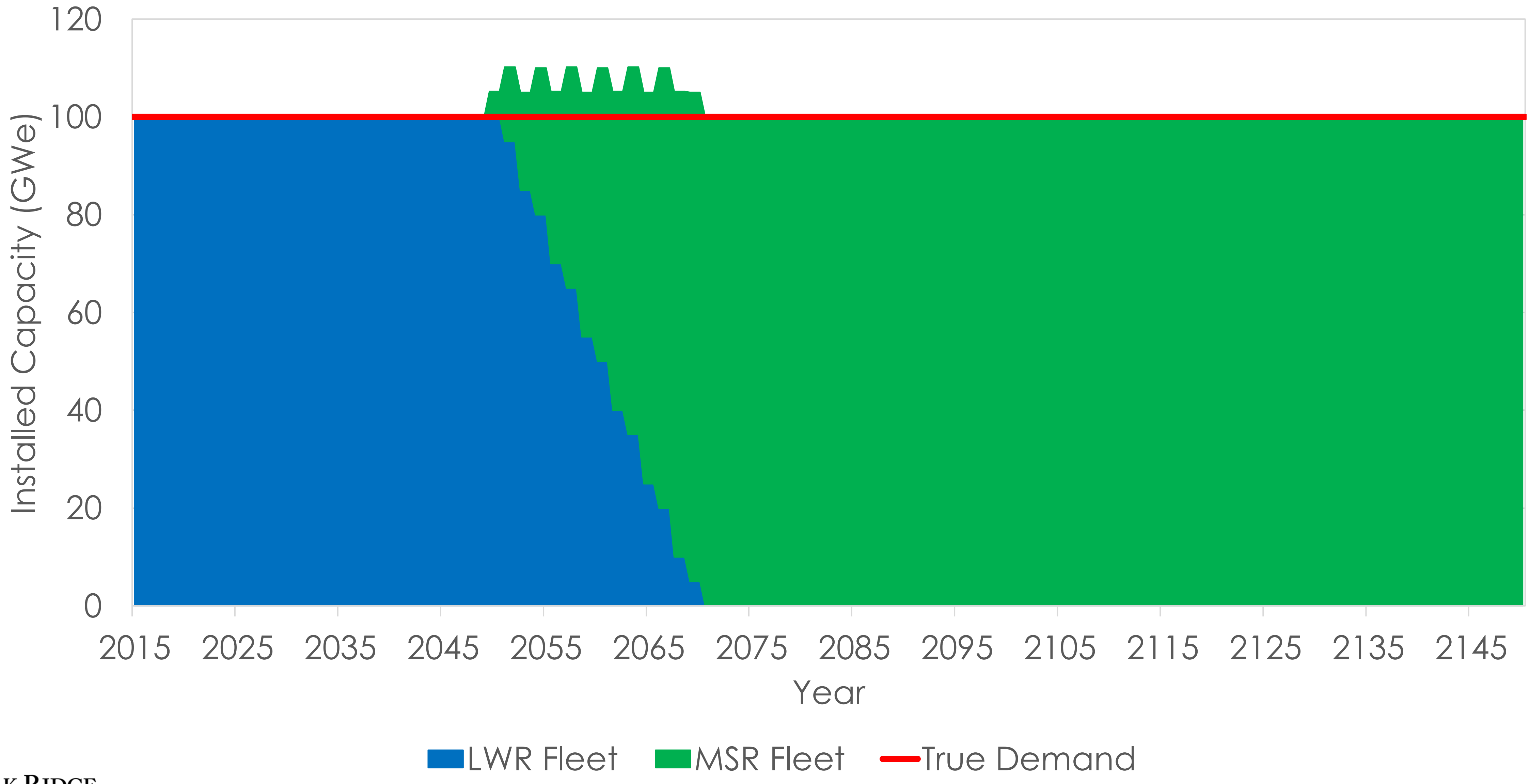
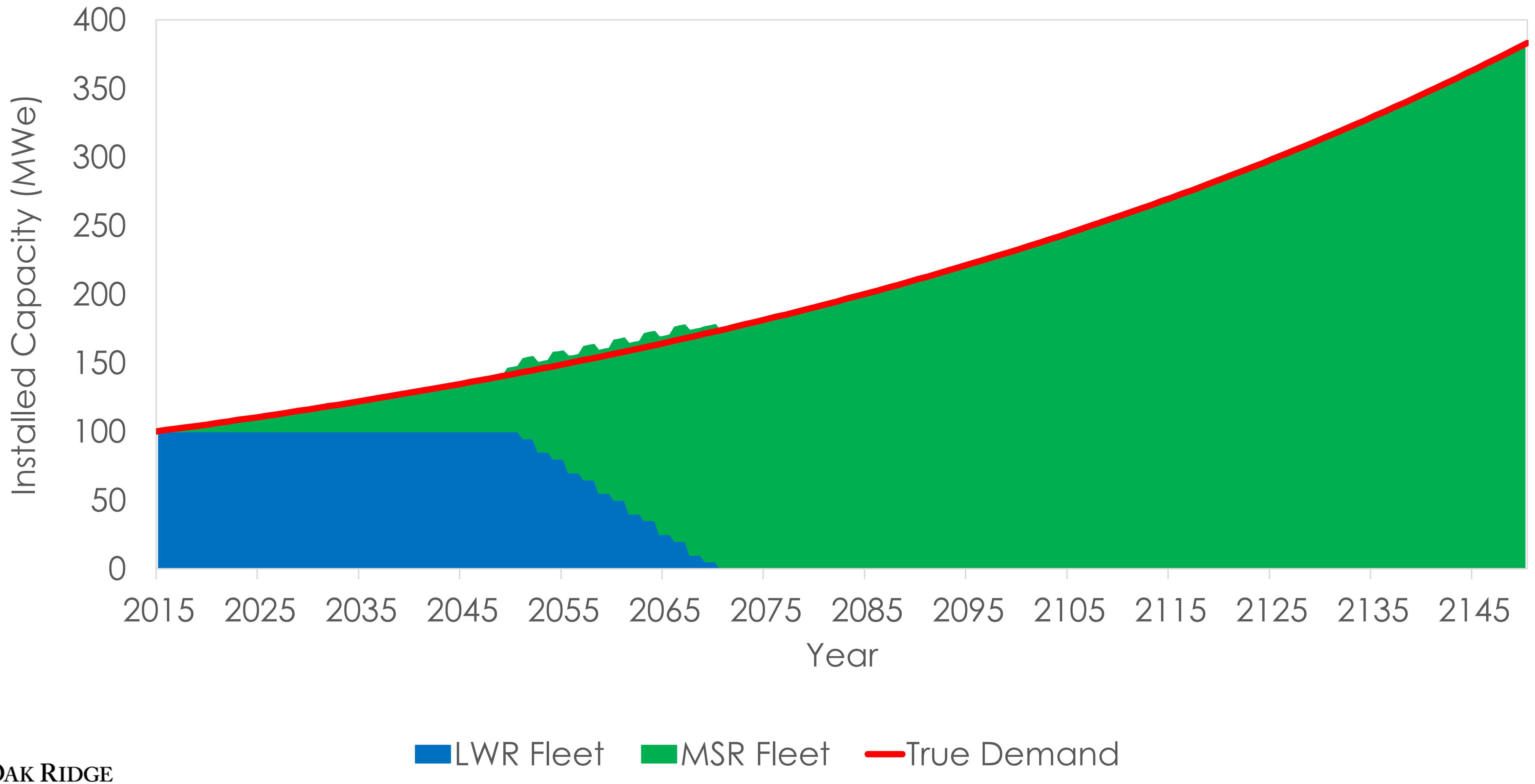
No Capacity Growth



1% Capacity Growth



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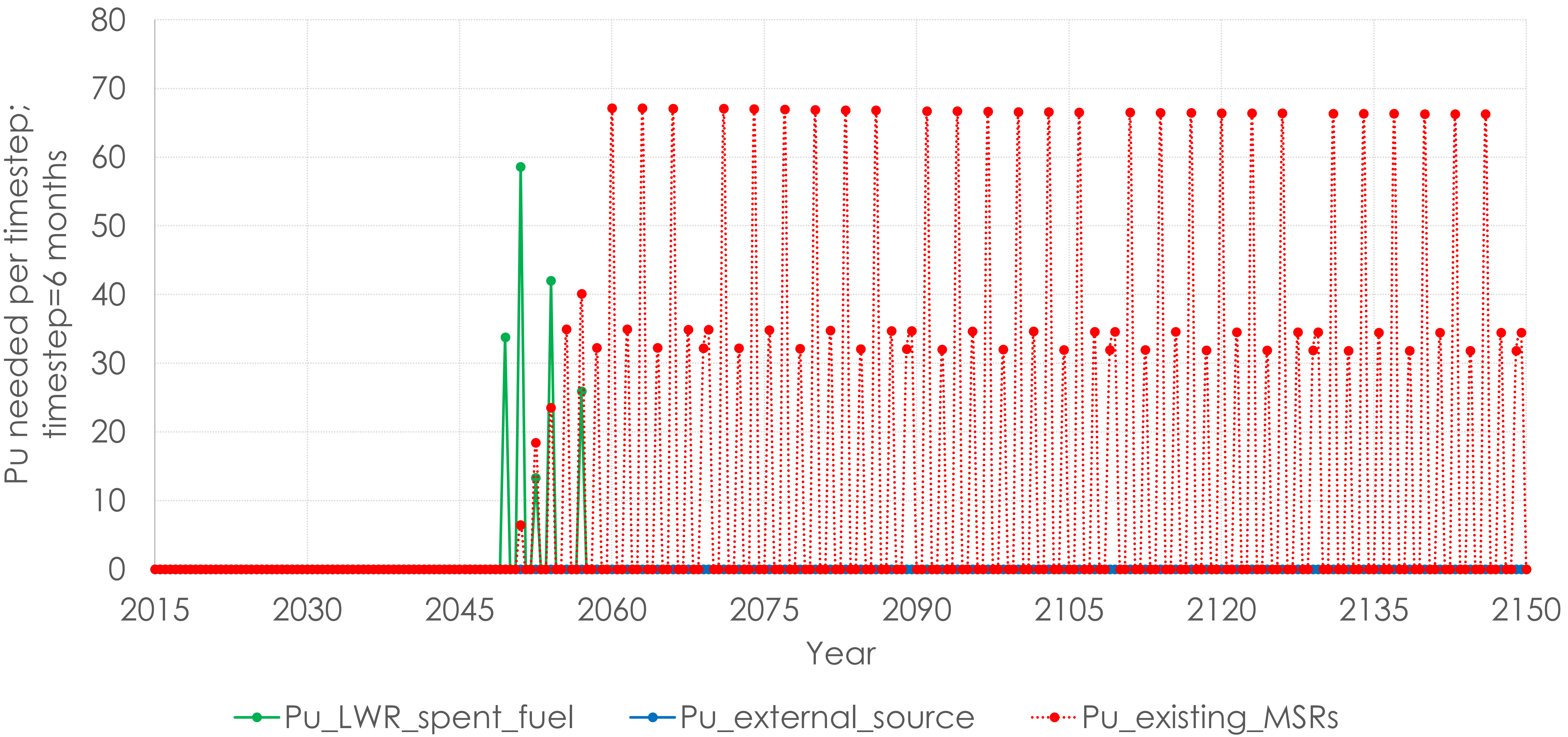
No Capacity Growth: Pu Sources For Deploying New FMSRs



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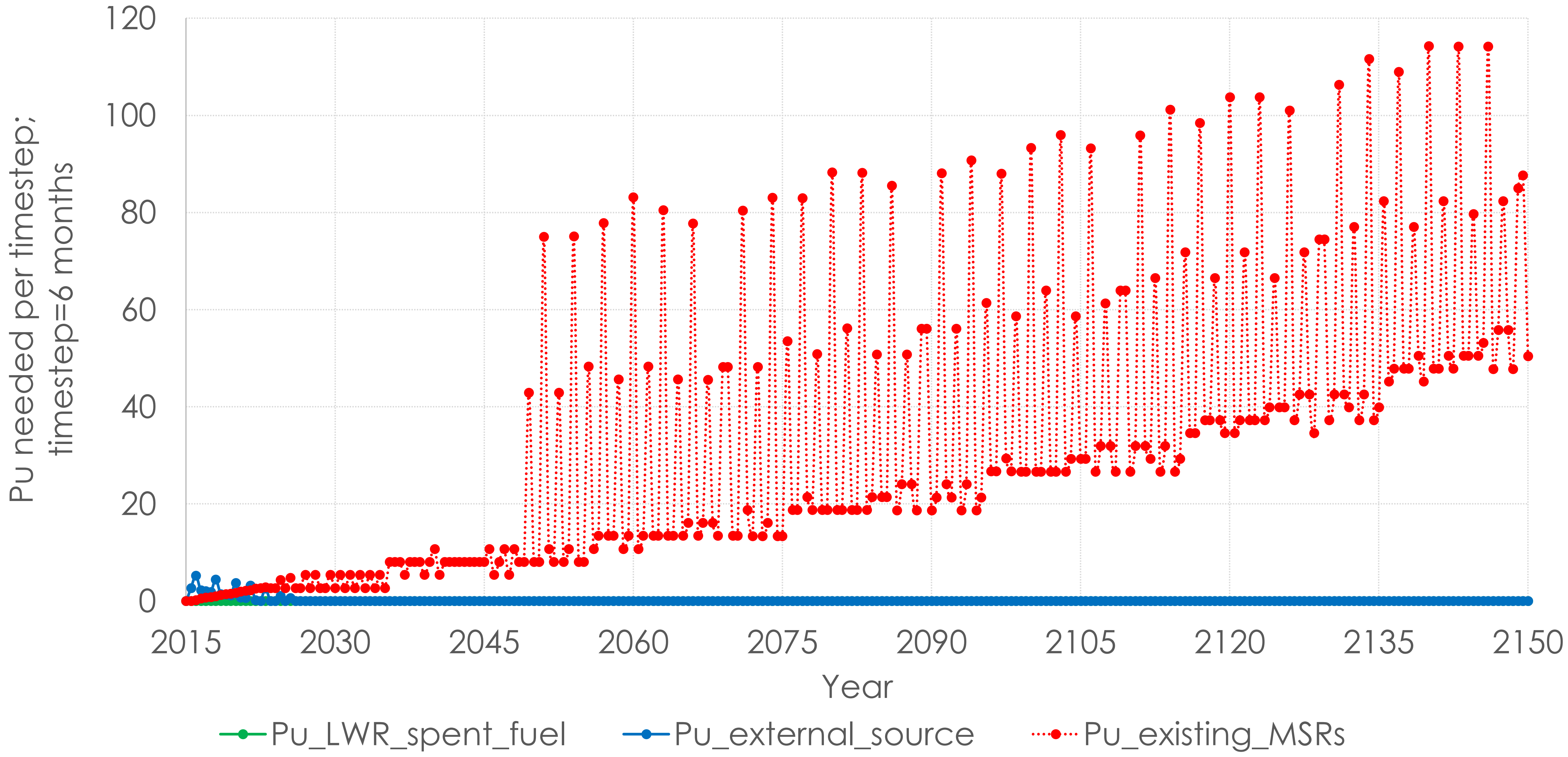
1% Capacity Growth: Pu Sources For Deploying New FMSRs



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HYPOTHESIS

- Previous analyses showed there was some delay in deploying SFRs due to material availability (FCO Campaign)
  - Led to the use of LEU fuel for startup as an option
- Why is the fast MSR deployment so efficient?
- **All excess Pu in FMSR is used to deploy new FMSRs (no Pu required for refueling)**
- **Using excess Pu in SFRs to refuel existing SFRs would slow down deployment**
- **External cycle time, and fuel residence time in SFR also slow down their deployment**
  - **Not an issue for FMSRs**

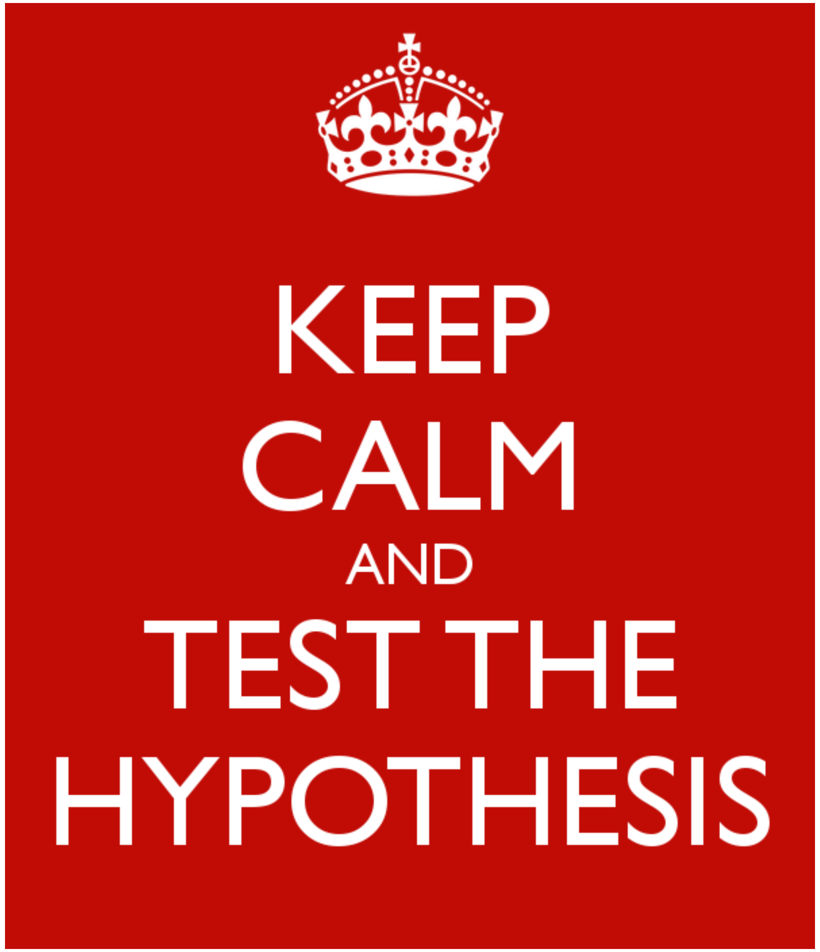

Image from: http://workingwithmckinsey.blogspot.com/2014/02/Being-Hypothesis-Driven.html

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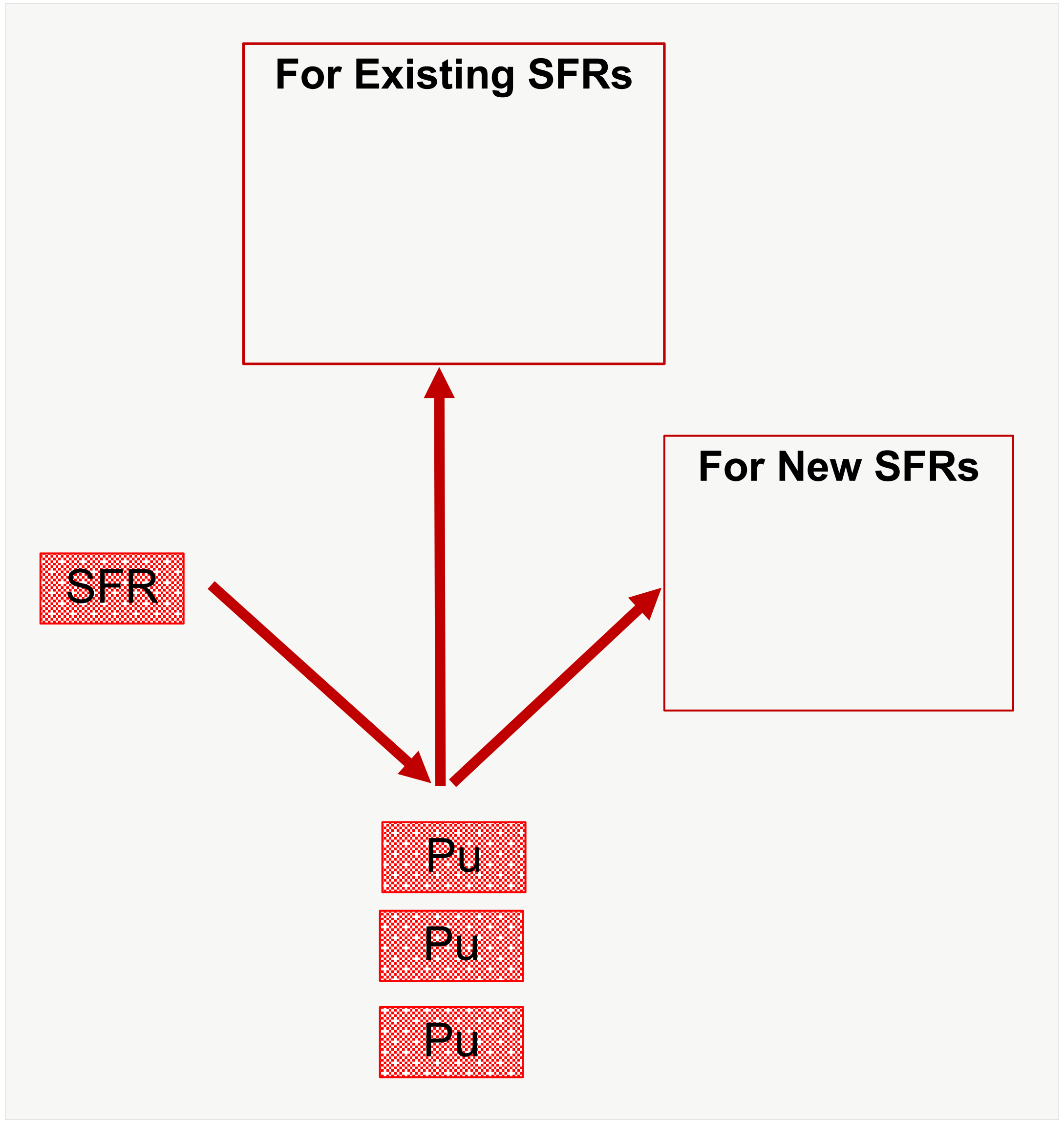
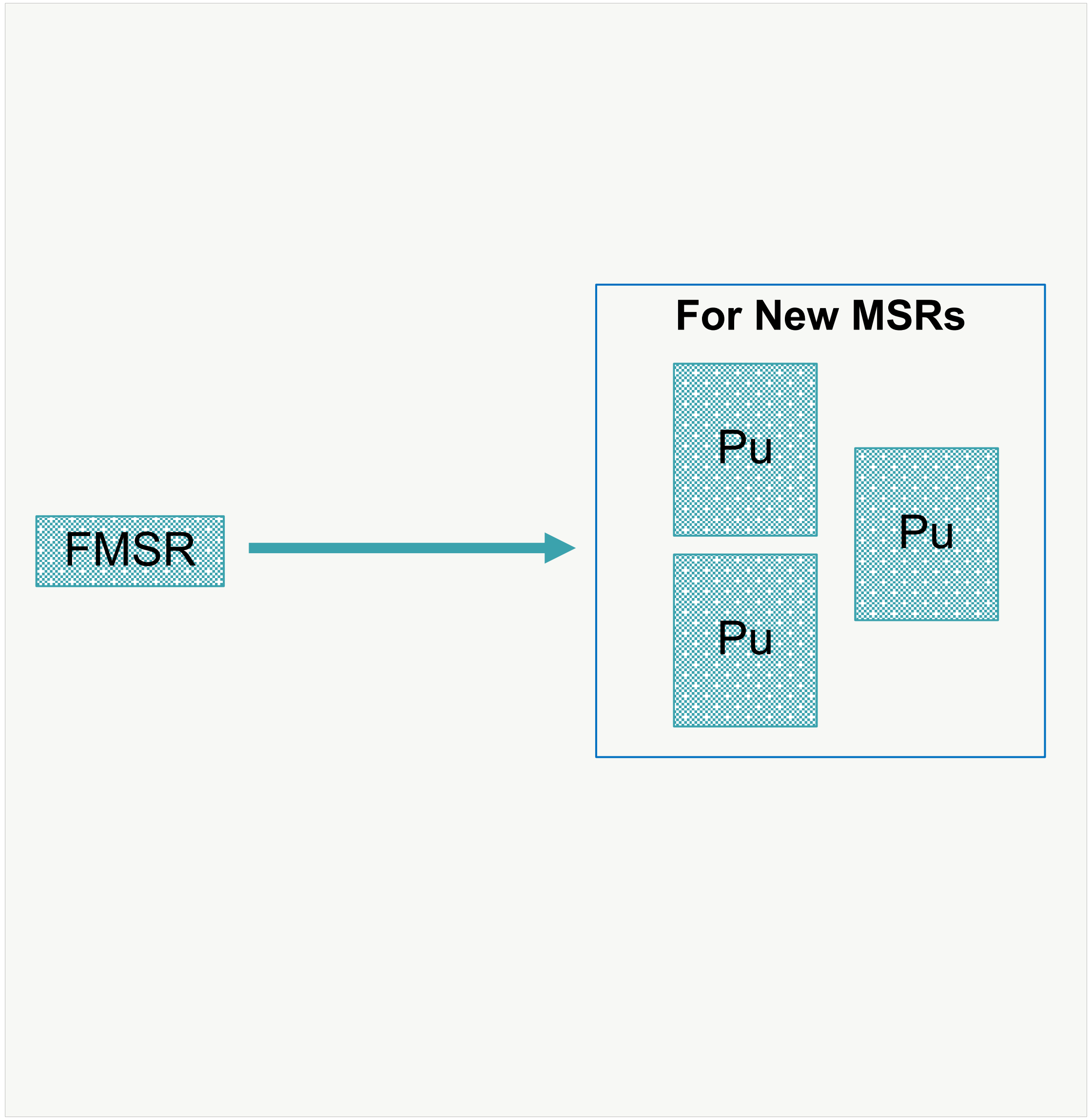
Cartoon: Accumulation of Pu in SFR and FMSR each year

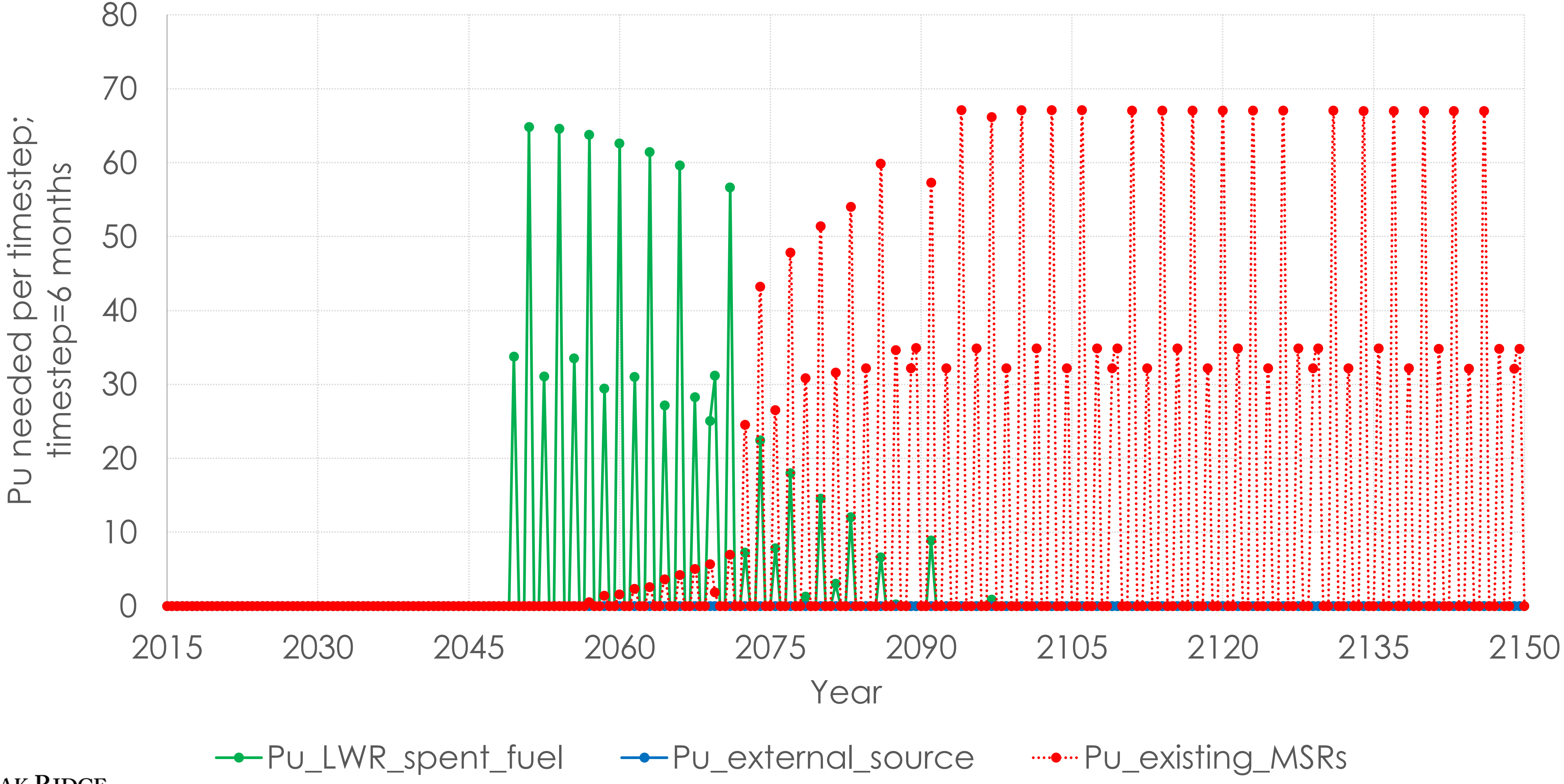




Testing the hypothesis

- Holds and delays were introduced into the transition to study if the transition would be delayed
- Assumed that ~85% of the Pu generated in the FMSR is held and only ~15% is released for building new FMSRs
  - Similar to SFR studied in the Fuel Cycles Options Campaign
- Delay before the salt is released through the loop again
  - Additional delay of **7 years** through the continuous loop (**5 years** for fuel residence time and **2 years** for external cycle time)

No Capacity Growth: Pu Sources For Deploying New FMSRs



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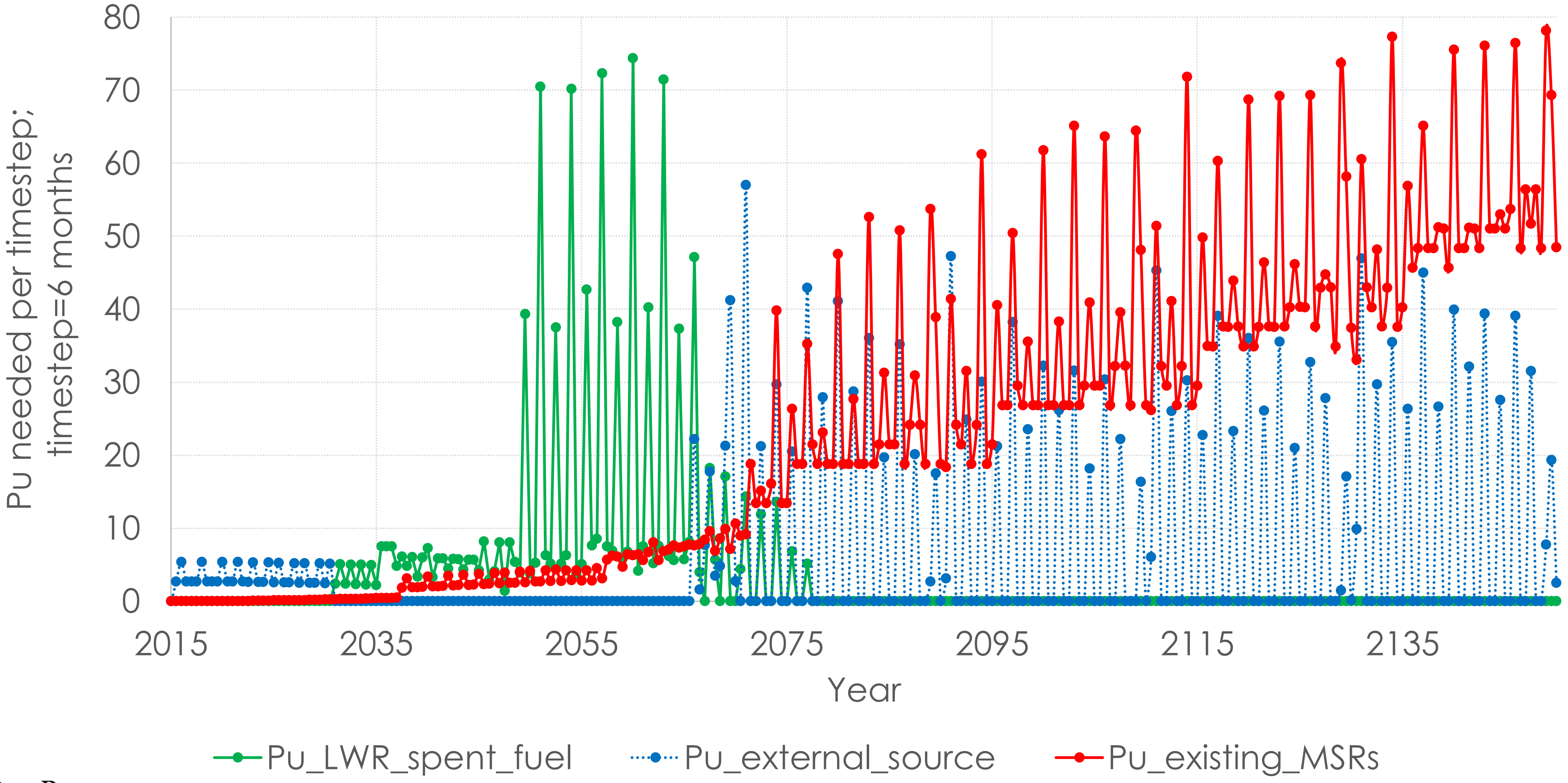
1% Capacity Growth: Pu Sources For Deploying New FMSRs



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Key Conclusions

- ORION accurately models MSR fuel cycles
  - Compared single FMSR ORION model to ChemTriton FMSR model
- This analysis demonstrated potential fuel cycle benefits using a FMSR
  - Low excess reactivity and continuous refueling increases the overall resource utilization
  - MSR fuel can achieve an almost zero out of core time when compared with an SFR where delays due to cooling, reprocessing and fuel fabrication are required
- The fast MSR studied in this work does not require any additional Pu while operating during its 20-year core lifetime
  - Any additional Pu produced in an SFR is used to create new fuel for existing SFRs **and** for building new SFRs
  - **All** the additional Pu produced by an MSR is available for building new MSRs
- ***Material availability for FMSRs could potentially make their deployment fast and efficient***

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Acknowledgements

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- We would like to thank Jeffrey Powers (ORNL), Edward Hoffman (ANL) and Bo Feng (ANL) for their feedback and lively discussions