U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Reassessing Methods to Close the Nuclear Fuel Cycle

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Systems Analysis & Integration Campaign

TWOFCS Workshop

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Introduction

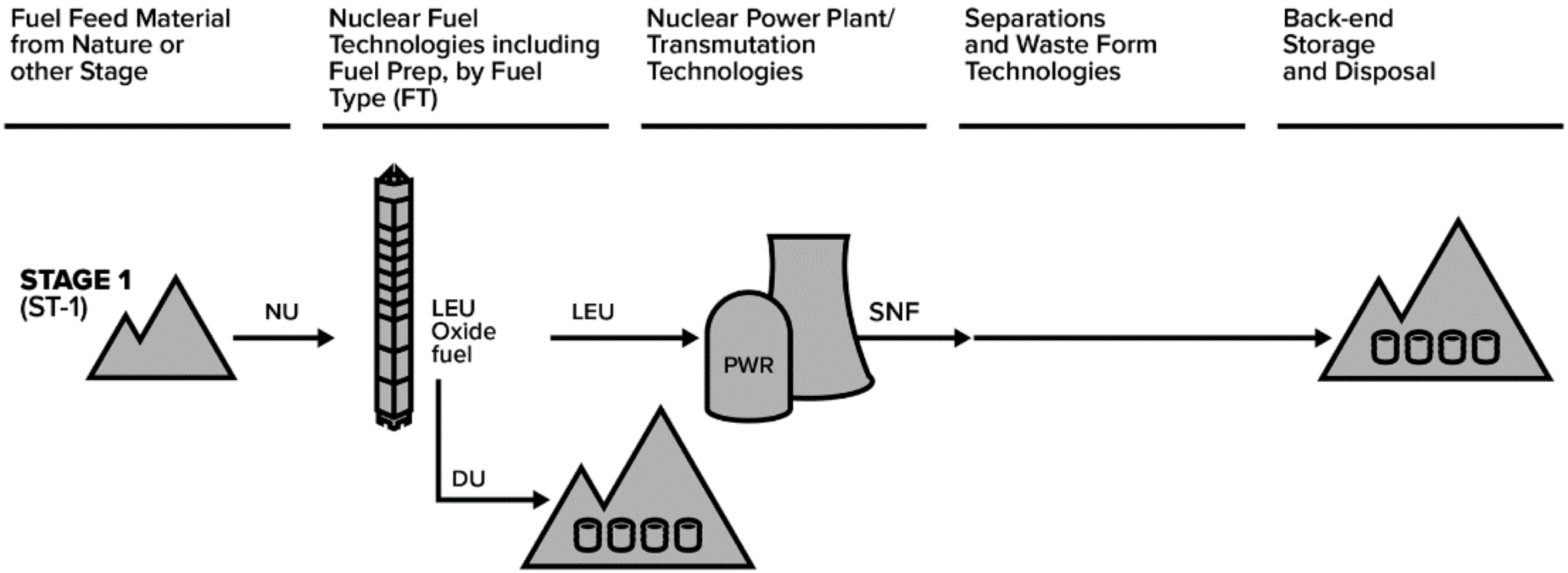
- **Context of Work:**
  - Work supported by DOE-NE Systems Analysis & Integration Campaign; 2014 Evaluation and Screening Study identified most promising fuel cycles as those with continuous recycle of U/TRU or U/Pu in fast spectrum reactors → 2014-2018 we investigated how we would transition to these end-states
  - The assumed end state is a closed nuclear fuel cycle (continuous recycle of all U/Pu or U/TRU) and elimination of the enrichment (maximum fuel utilization)
  - U.S. based scenario (no recycle infrastructure currently exists)
  - Task was to identify issues and challenges of transition from the current conditions to the desired end state (multiple end states have been studied) and approaches to address them
  - Study utilized subject matter expertise, simple analyses, and detailed analyses using fuel cycle simulation codes such as DYMOND, ORION, and VISION.

- **Goals of Presentation:**
  - Summarize some of the key findings of the last few years of transition analysis
  - Provide examples of answers that our potential customers (governments) are seeking from our expertise and tools

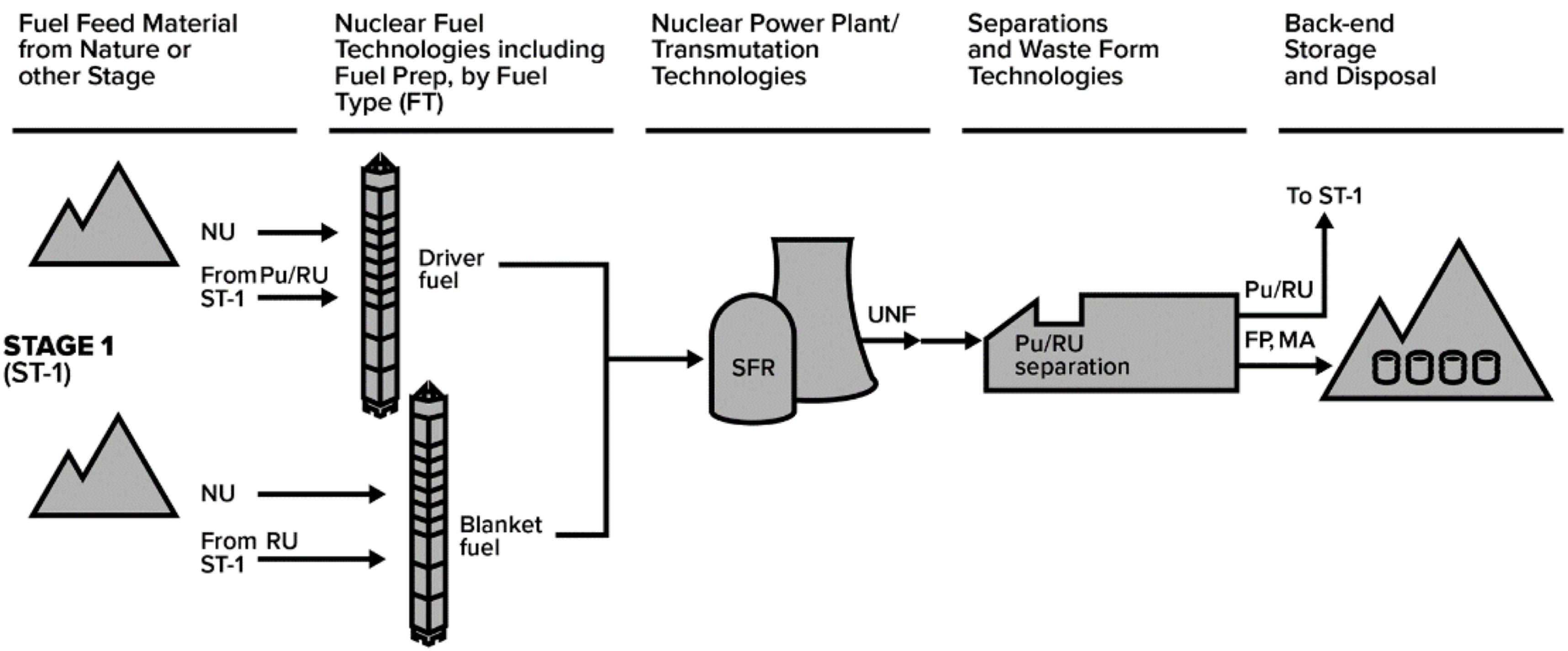
Existing Infrastructure

- **Large fleet of light-water reactors (99 in operation + 2 under construction)**
  - Most scheduled to shutdown in 2030 to 2050 timeframe
  - LWR lifetimes could be extend to 80 years (most currently licensed to 60 years)
    - *Current issues regionally with large penetration of natural gas and wind posing economic challenges to existing fleet– makes new builds economically impossible*
- **Large inventory of used fuel in storage (~85,000 MTIHM)**
  - Producing about 1,800 MTIHM/yr
- **No commercial recycle technologies currently exist**
- **All enrichment capacity currently limited to <5%**

Once-Through Cycle
Current Systems Minus Disposal



Fast Reactor Closed Cycle Example End State



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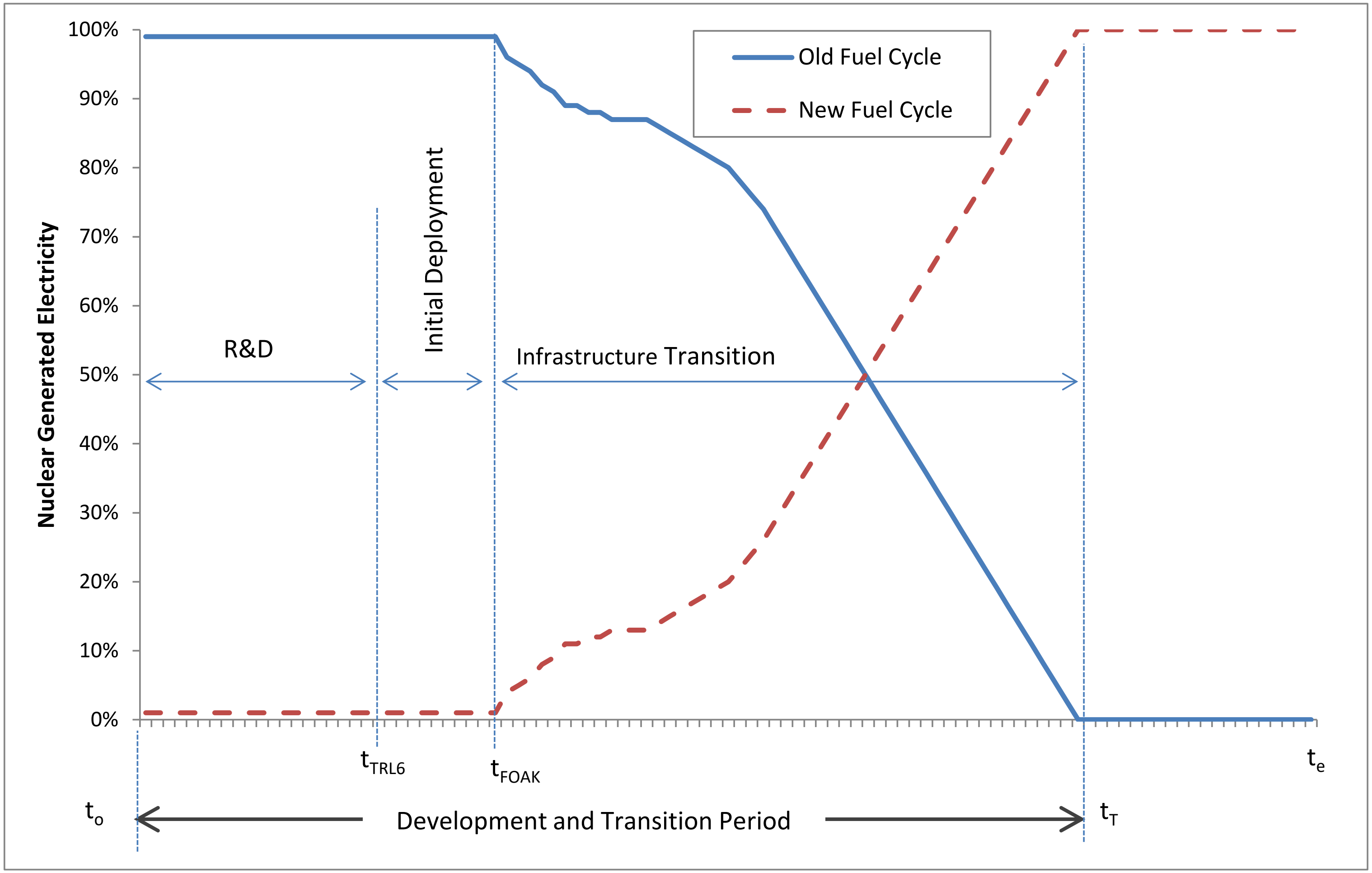
Conceptual transition time profile Transition to 100% Fast Reactors



Note: It is possible to produce a closed fuel cycle with a mixed system of fast and thermal reactors with a fleet ratio as high as 2:1

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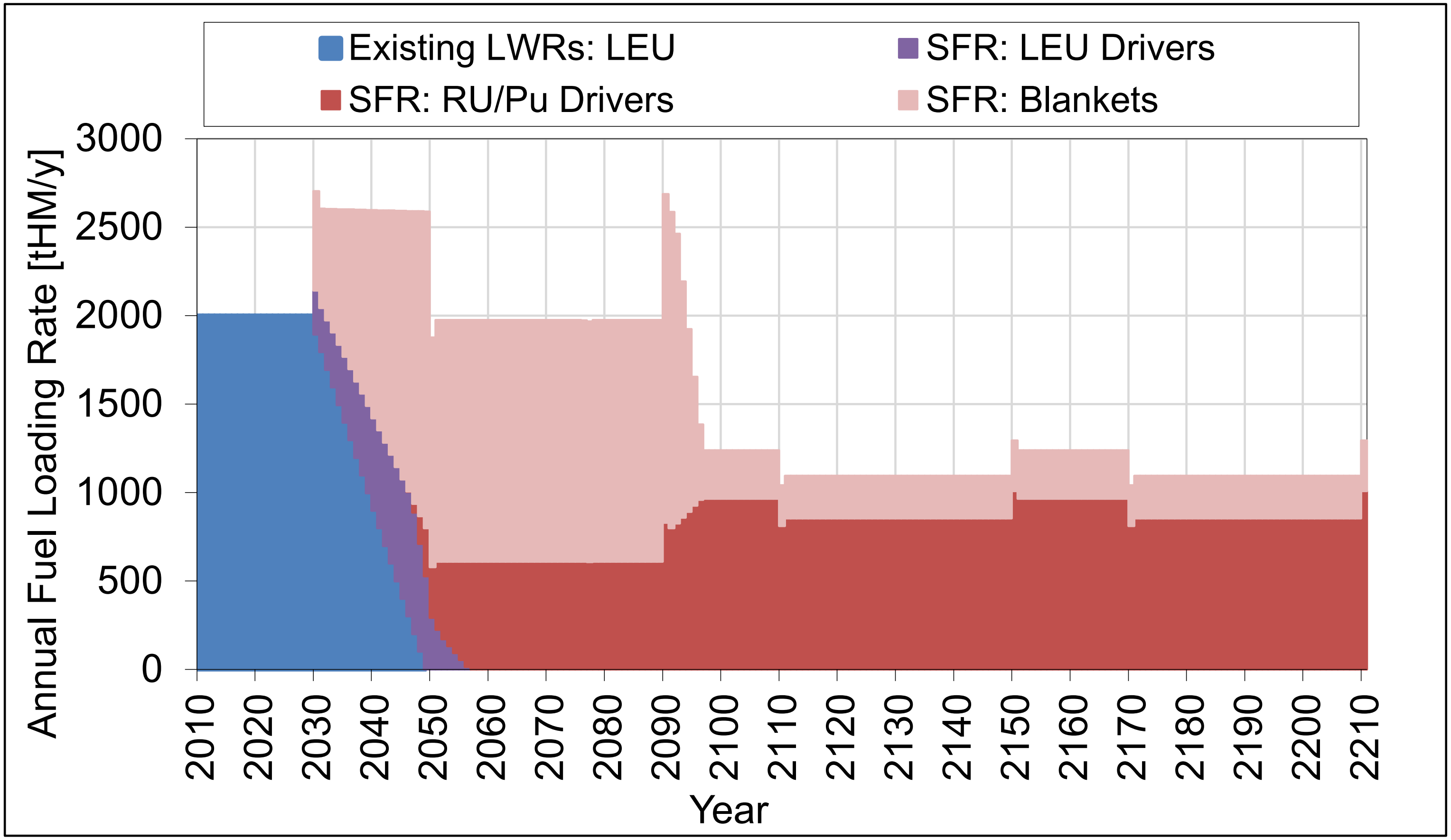
Example of Detailed Calculations

- **LWR Pu Startup of High Pu Production SFRs (Scenario 23B)**



Findings
NU and HLW/SNF

- **Natural uranium use for current system is about 190 MT per GWe-yr and is reduced to about 1 per GWe-yr for the fast reactor closed cycle**
  - For deployment with HALEU requires a large initial input of NU
  - However, the benefits accumulate as more recycled fuel is used
- **Reduction in the amount of waste requiring geologic disposal occurs on paper as soon as a decision is made to recycle used fuel, and is physically realized when recycling begins**
  - If plutonium is used, the full benefit is achieved as soon as the recycling capacity exceeds the rate of used fuel generation, which may occur even before the first fast reactor is completed
  - If enriched uranium is used, the benefit will be incurred gradually as the transition proceeds and thermal reactors are phased out. The full benefit is achieved when enrichment is no longer required
  - The shorter the transition time, the earlier the full benefit is achieved

Findings
System Material Inventories

- **System material inventories are determined by the design of the reactors, average discharge burnup, and recycle system design**
  - Specific power density is a major driver of system inventories
    - *Thermal efficiency, capacity factor, and other reactor design/operation are important*
    - *Evolution of fuel composition can add a significant dynamic component (more fissile to compensate)*
  - Higher burnup reduces refueling requirements and inventory in the recycle system
  - The recycle time is a key factor in system inventory
    - *Offsite – typically at least 5 years of cooling before offsite shipment*
    - *Onsite – typically one cycle of cooling for electrochemical*
    - *Integrated – very short– recycle inventory essentially part of startup inventory (molten salt)*
  - The total fissile inventory determines the external requirements
  - <u>The initial startup inventory represents the large initial demands that is a challenge for rapid expansion of new capacity</u>

$$I_{FR} = I_{core} + I_{excore}$$

$$I_{core} = \frac{M_{core}}{P_{th}\,\eta_{elec}\,CF}$$

$$I_{excore} = \frac{T_{excore}}{BU}$$

Findings
Transition and Growth Fissile Limits

- **During transition, growth is limited by the rate at which external fissile material can be acquired**
  - Complex set of technical and practical limitations
  - HALEU – practical limits on deployment of enrichment capacity
  - LWR UNF – practical limits on deployment of recycle capacity and technical limits on inventory and generation rate
  - FR Breeding – practical limits on FR capacity and recycle capacity and technical limits on breeding rates
    - *Capacity grows as the need shrinks*
    - *Sets sustainable growth rate without outside fissile supplies*
- **The greater the amount of fissile material required per reactor, the lower the sustainable growth rate**
  - Maximum breeding rate and recycle time are also important factors
  - Also affects the amount of HALEU and/or recycled LEU LWR UNF required during transition

Findings
HALEU vs LEU LWR UNF

- **This study found that transition can be achieved in the U.S. via thermal reactor used fuel in zero or low growth scenarios.**
  - To obtain enough material to start one gigawatt of breakeven fast reactors requires separating over 500 MT of thermal reactor used fuel while the breeder/burner system would require nearly 800 MT.
  - This separation capacity must be installed and operational well before the fast reactor fleet
    - *Represents significant economic challenges because of early low demand relative to the economic scale for recycle system – expect low capacity factors or economically undersized facilities early in transition and large capital investments with no operating customers at start of operation*
    - *Tight coupling between recycle and fast reactor systems*
    - *Single source of fissile material – risk of plant shutdown*
- **The use of HALEU to start up fast reactors was found to decouple much of the system and alleviate or completely eliminate most of the transition constraints**
  - Recycling of thermal reactor used fuel becomes optional
  - When using HALEU, the only new technology required to start transition is fast reactors
  - Fresh HALEU fuel has a long shelf life, allowing prefabrication and storage of contingency fuel to protect against any disruptions in the rest of the fuel cycle
    - *Less political concerns with storage of HALEU relative to U/Pu*

Conclusion

- **Multi-year effort required significant analysis with and without fuel cycle simulations, resulted in major conclusions:**
  - The shorter the transition time to a closed cycle, the earlier the full benefit is achieved
  - Fissile requirements in the first core loads of FRs can make or break the transition, they must be modeled accurately
  - FRs can be designed to achieve better transition performance for a fleet, they were traditionally designed for equilibrium performance (single reactor)
  - Starting Fast Reactors with HALEU is practical and may be more advantageous in terms of fuel cycle benefits compared forcing the first FRs to depend on recycled LWR UNF
- **Other takeaways from this study:**
  - Customer needs to be informed on consequences of various decisions that can be stated with confidence → generalizations are difficult to ascertain but are necessary
  - Level of detail from fuel cycle simulations may not be appropriate for most decision makers and stakeholders
  - Development of fuel cycle simulation tools may need to be targeted at the customer rather than for the sake of advancing the science

RP Load Factors