December 8, 2020

Brent Dixon
Deputy National Technical Director
Systems Analysis and Integration

Economics of Future Fuel Cycle Options

Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and Waste Aspects of Advanced Nuclear Reactors

Idaho National Laboratory

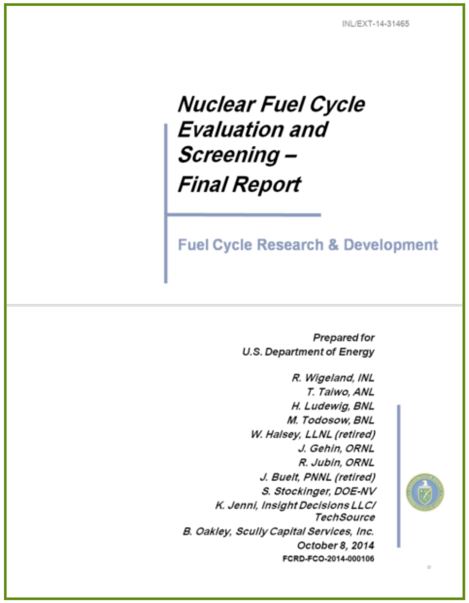
INL/EXT-20-60574

Overview

- Sustainable Nuclear Fuel Cycles
- Characteristics of Promising Fuel Cycles
- E&S Study Evaluations Related to Costs
- Levelized Cost of Electricity at Equilibrium
- Costs During Transition
- Summary

Sustainable Nuclear Fuel Cycles

- **Sustainable fuel cycles have sometimes been defined as those that:**
  - Improve uranium resource utilization
  - Maximize energy generation
  - Minimize waste generation
  - Improve safety
  - Limit proliferation risk
- **E&S study** (https://fuelcycleevaluation.inl.gov/SitePages/Home.aspx) **showed that fuel cycles different from the current fuel cycle could achieve substantial improvements**
  - Reducing waste generation
    - Less than 1/10 the mass of long-lived, highly radioactive hazardous materials for disposal
    - Less than 1/1000 the mass of uranium going to waste
  - Increasing efficiency of using fuel resources
    - From today's use of only 0.6% of the uranium to nearly 100%, more than 100 times better


INL/EXT-14-31465

Nuclear Fuel Cycle Evaluation and Screening – Final Report

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy

R. Wigeland, INL
T. Taiwo, ANL
H. Ludewig, BNL
M. Todosow, BNL
W. Halsey, LLNL (retired)
J. Gehin, ORNL
R. Jubin, ORNL
J. Buelt, PNNL (retired)
S. Stockinger, DOE-NV
K. Jenni, Insight Decisions LLC/ TechSource
B. Oakley, Scully Capital Services, Inc.
October 8, 2014
FCRD-FCO-2014-000106

Characteristics of Promising Fuel Cycles

- **Characteristics of systems capable of providing significant improvements**
  - Recycle of irradiated fuel
    - Processed to recover useful fuel materials
    - HLW from processing is disposed in a repository, not spent fuel
  - Fast neutron spectrum reactors
    - Fast neutron spectrum fission/capture characteristics are more favorable for sustainable use of fuel resources with either uranium or thorium-based fuel cycles, with the most promising options using uranium
    - Thermal neutron spectrum reactors may also be used with a thorium-based fuel cycle, but it is more challenging than using a uranium-based fuel cycle in a fast neutron spectrum reactor
  - Eliminate the need for uranium enrichment
    - Depleted uranium from existing inventory can be used for fuel instead of being disposed as waste
      - Over 700,000 tons in storage at this time in the U.S. could provide fuel for many centuries

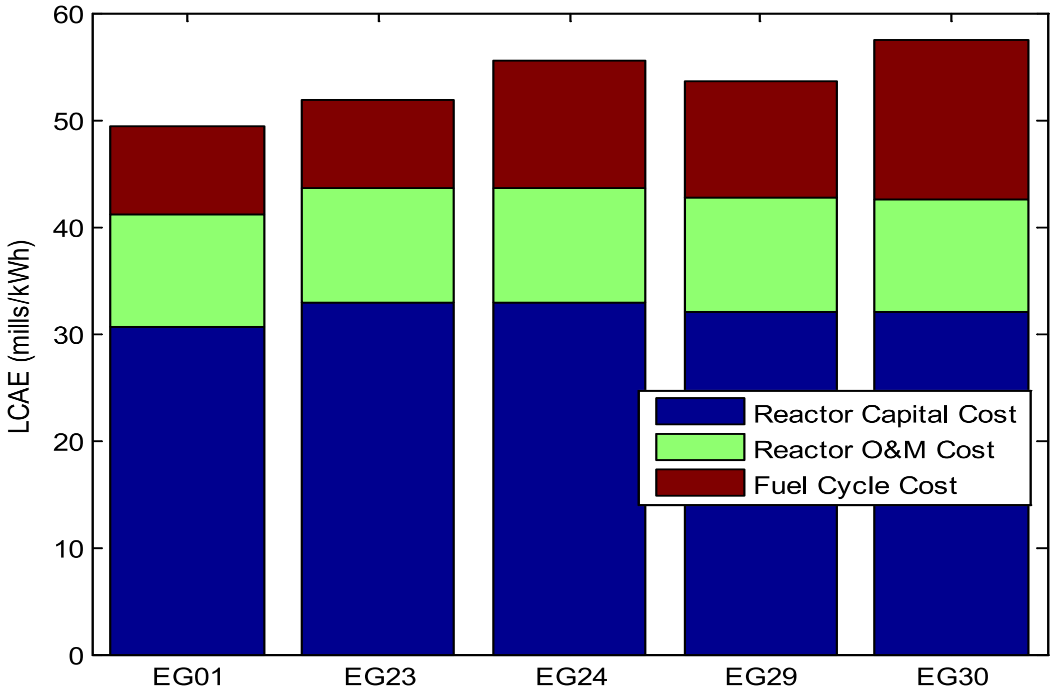
E&S Study Evaluations Related to Costs

- **Two Evaluation Criteria: Development and Deployment Risk, Financial Risk and Economics, and the associated metrics informed on financial risk and costs**
  - Development and Deployment Risk
    - Development cost
    - Development time
    - Deployment Cost from Prototypic Validation to FOAK Commercial
    - Compatibility with the Existing Infrastructure
    - Existence of Regulations for the Fuel Cycle and Familiarity with Licensing
    - Existence of Market Incentives and/or Barriers to Commercial Implementation of Fuel Cycle Processes
  - Financial Risk and Economics
    - Levelized Cost of Electricity at Equilibrium (LCAE)
- **A third Evaluation Criterion, Institutional Issues, was also specified by DOE/NE, and was informed by three of the metrics developed for Development and Deployment Risk**

Levelized Cost of Electricity at Equilibrium

- **Cost estimates for electricity generation were developed to inform on the relative cost and benefits of alternative fuel cycles**
  - Cost / price information was based on historical data and the Advanced Fuel Cycle Cost Basis report (INL/EXT-07-12107, 12/2009 with updates)
  - Specialized computer code, NE-COST, was used to calculate Levelized Cost of Electricity at Equilibrium (LCAE)
    - Calculated for fuel cycle mass balance equilibrium, i.e., all the mass flows and characteristics do not change with time, or from one irradiation cycle to next
    - Calculates mean values and uncertainty distributions for electricity costs (includes construction, financing, O&M, …)
    - Models the complete fuel cycle from mining to disposal
- **LCAE results were not used as part of the process to identify the promising fuel cycles, but were provided as additional information for decision-making process**
  - Based on a recommendation by a separate panel of experts due to the uncertainty of such estimates

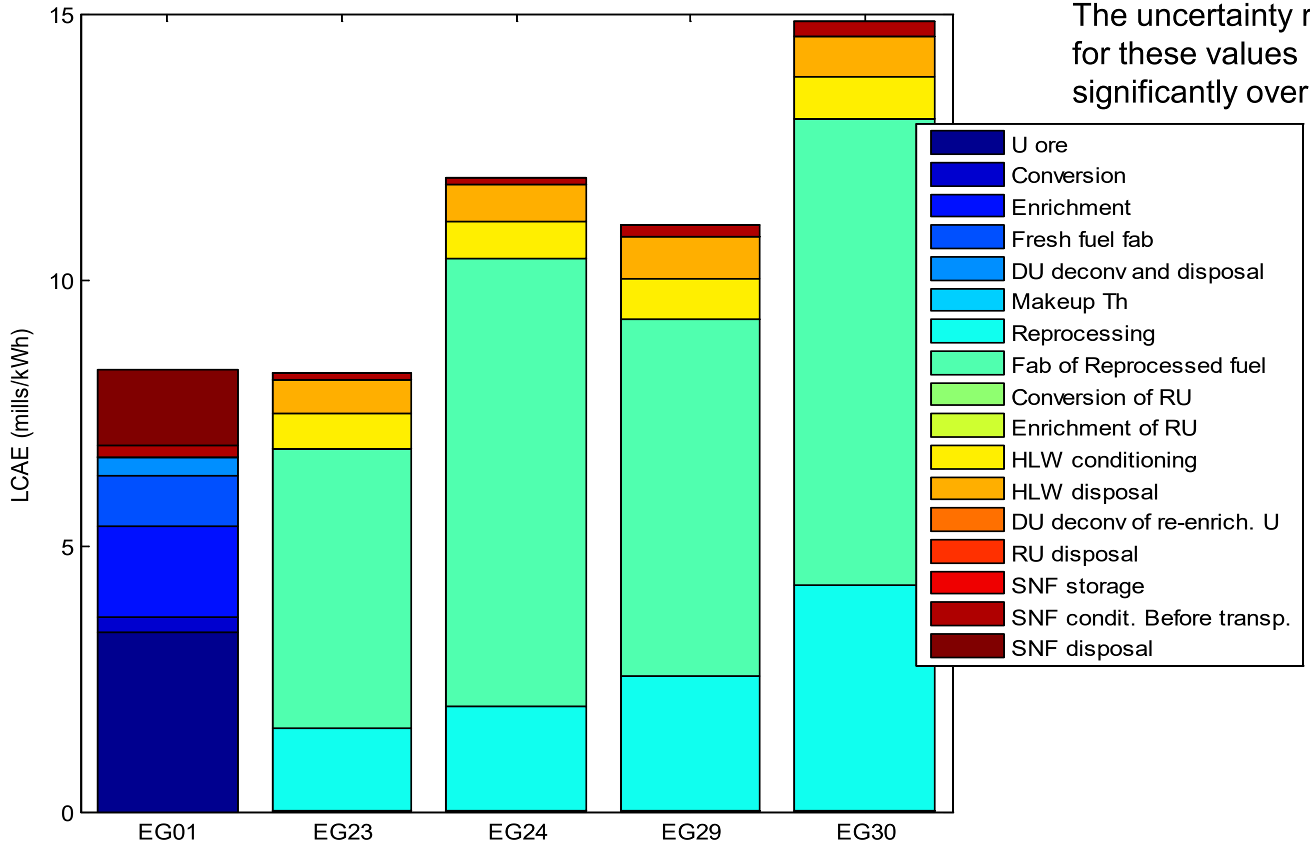
LCAE for the Most Promising Fuel Cycles



The uncertainty ranges for these values significantly overlap

- EG01 Once-through using enriched-U fuel in thermal critical reactors
- EG23 Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors
- EG24 Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
- EG29 Continuous recycle of U/Pu with new natural-U fuel in both fast & thermal reactors
- EG30 Continuous recycle of U/TRU with new natural-U fuel in both fast & thermal reactors

Non-reactor Contributions to LCAE



The uncertainty ranges for these values significantly overlap

- **Recycle fuel cycles have reprocessing activities replace front-end activities associated with obtaining new uranium for fuel**
  - For U/Pu recycle in fast reactors, essentially no change in LCAE from non-reactor contributions

Cost of Promising Recycle Fuel Cycles

- **For the most promising recycle fuel cycles, the cost difference compared to the current U.S. fuel cycle may be small**
  - For U/Pu recycle in fast reactors, the difference is due to the estimated higher cost for fast reactors
  - For U/TRU recycle in fast reactors, the potentially more complex reprocessing and the need for greater shielding for fabrication of the recycle fuel add to the costs
  - **Uncertainty is large**, and lower costs are possible
    - Advanced technologies/materials could improve thermal efficiency, but lower maturity increases cost uncertainty

Fuel Cycle Group Analysis Example LCAE ($/MWh)

Fuel Cycle Group		Mean LCAE	2 x Standard Deviation
EG01	Once-through using enriched-U fuel in thermal critical reactors	49.4	11.1
EG23	Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors	51.9	15.4
EG24	Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors	55.5	15.8

Costs During Transition

- **The costs of transition are currently being investigated, and to date, the following observations have been made**
  - **All of the promising options will require mostly new infrastructure to support the fuel cycle, including new types of reactors, reprocessing facilities, and recycle fuel fabrication capabilities**
  - **Ability to effectively use facilities during transition has a significant cost impact**
    - E.g., if a reprocessing facility is built larger than initially needed to accommodate increasing demand as transition continues, the capacity factor in the earlier years is low, with a detrimental impact on costs
    - Alternately, incremental addition of smaller facilities may lose economies of scale
  - **Amount of time that used fuel stays in storage outside of the reactor awaiting processing also has a significant effect on cost**
    - The longer the time needed before reprocessing, the larger the on-site inventory, which increases fuel costs but also may lengthen the time required for transition depending on the source of fissile materials supporting the transition
    - Use of HALEU during early deployment enables decoupling of reactor startup from reprocessing startup

Summary

- **Most promising fuel cycles for R&D have following characteristics**
  - Recycle
  - Fast neutron spectrum reactors
  - Elimination of uranium enrichment
- **Costs for operating such fuel cycles may be close to costs for current U.S. fuel cycle, depending on availability of cost-effective technologies**
- **Cost of transition to one of the most promising fuel cycles also depends on balancing the increasing need for infrastructure as transition proceeds and the effects on overall cost by having underutilized facilities early in the transition**
  - Shorter time out-of-core is beneficial
  - Fast reactor startup on HALEU may be preferable to using U/Pu recovered from used LWR fuel by decoupling fissile availability from reprocessing capacity growth, and a combination of the two may provide the best approach

Idaho National Laboratory