CLOSING THE NUCLEAR FUEL CYCLE USING MOLTEN SALT REACTOR TECHNOLOGY

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Abstract

1. INTRODUCTION

The United States currently operates 94 commercial reactors with a combined installed capacity of 97 GWe. In 2024, nuclear energy accounted for 18.6% of the nation's total electric energy generation. To date, the current and historic US reactor fleet (of which an additional 38 commercial plants were once operated but are now permanently closed) has generated more than 90,000 MTHM (metric tons of heavy metal) of commercial spent nuclear fuel (SNF) since the 1950s. This inventory continues to grow at about 2,000 MTHM per year for at least two more decades. Although spent nuclear fuel inventory continues to be stored and managed safely, it remains a liability and needs to be managed appropriately, when and how is yet to be decided. With advanced reactor technologies such as molten salts reactors (MSR), several options are available for the management of used nuclear fuel and MSR technology has major role to play in closing the nuclear fuel cycle thus contributing to its sustainability.

Once through fuel cycle in the U.S.

The current U.S. nuclear fuel cycle (Fig. 1) is a once-through fuel cycle using enriched uranium fuel (3-5%) in light-water reactors (LWR). The fuel cycle is not yet complete, and disposal paths for spent fuel and depleted uranium are not currently implemented (Fig. 1). The present U.S. fuel cycle generates two major waste streams requiring geologic disposal or similar isolation, along with low- level waste.

- 2,000 MT per year of spent fuel with a current plan for a final disposal geologic repository
- 16,000 MT per year of depleted uranium, with no disposal path identified at this time, but it will also require long-term isolation due to buildup of radioactive decay products

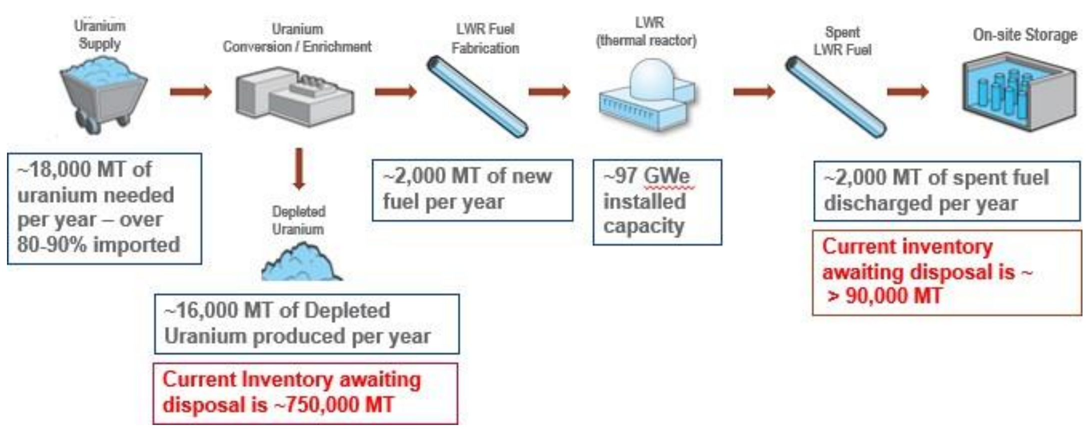

FIG. 1: Current U.S. Fuel Cycle Performance [1]

Several options are available for the management of used/spent nuclear fuel which are either dry cask storage for the next 300 years followed by deep geological disposal for spent nuclear fuel (SNF), reprocessing and recycling of used nuclear fuel (UNF) using either an aqueous PUREX-type process or pyroprocessing technology, or as new MSR concepts are being proposed and developed where spent Light Water Reactor (LWR) fuel is recycled for use as fuel salt. This concept allows for regenerating the carrier salt with fuel composition adjustment along with recovery of fissionable radionuclides. As of today, none of these alternatives are currently operational in the United States or in the world while policy, technological, and regulatory challenges continue to be addressed.

Benefits of recycling

The development of new fuel cycle technology is a goal of the Department of Energy (DOE)-Office of Nuclear Energy (NE). This goal has been driven by the need to manage high-level waste, recover the energy value of spent fuel, and develop fuel cycles for next generation nuclear plants. An evaluation and screening study of nuclear fuel cycle options was conducted over three years and released in 2014 [2]. Nine evaluation criteria were specified by DOE-NE representing broadly defined economic, environmental, safety, non-proliferation, security, and sustainability goals. The fuel cycle options evaluated were comprehensive with respect to fuel cycle performance. Screening for potential benefits resulted in a smaller number of promising fuel cycle options that could achieve substantial improvements compared to the current open nuclear fuel cycle in the United States. Among all options, four groups of fuel cycles (Figure 2) consistently provided the highest improvements compared to the current once through fuel cycle in the U.S. and are described below.[9]

<u>Option 1 -EG 23</u> : Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors

<u>Option 2 – EG 24</u>: Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors

<u>Option 3 – EG 30</u>: Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors

However, these most promising groups exhibited differences with respect to the three challenge criteria, with EG23 estimated with lower development and deployment challenges than the other two due to the use of U/Pu recycle as compared to U/TRU recycle. When considering both benefits and challenges, another Evaluation Group was included as a most promising option that has comparable development and deployment challenge to EG23 and has almost the same potential benefit:

<u>Option 4 -EG 29</u>: Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors.

After the completion of this study showing that recycle of spent fuel would achieve improvement compared to the current once through fuel cycle, one could ask why it is in the U.S. national security interest to allow commercial recycling of UNF?

- It will provide a domestic supply of fuel for nuclear reactors (potentially for all kinds of reactors including LWRs, HWRs, SMRs, Gen IV reactors including MSRs) and will ensure low carbon power supplies. It will also, as found in Reference 3, eliminate the need for enrichment facilities to provide low enriched uranium (LEU). If the United States decides to deploy a fleet of fast reactors, analyses have demonstrated the importance of the availability of fissile material (U-235, and/or Pu-239) on appropriate timescales to start up and then continue to deploy new fast reactors. Fast reactor deployment and the associated reprocessing of the spent fuel would save more than 2 million tons of uranium ore, saving the US more than $100 billion in import costs (based on current ore prices), and would consume approximately 10% of the uranium tailings currently destined for disposal [4]. If the reprocessed uranium from the light water reactor spent fuel was recycled in MSRs, additional uranium ore would be saved.

- Recycling prevents the accumulation of a large stockpile of spent nuclear fuel which represents more than 90,000 MTHM. Reducing quantities of SNF stored in indefinite interim storage (dry and wet), will reduce security requirements for multiple widely distributed sites throughout the United States. Also recycling will avoid the need for the selection of a second repository. In addition, the security associated with placing all HLW in one repository as opposed to multiple sites is an important simplification.
- Recycling decreases the volume and radiotoxicity of the waste while reducing the overall environmental footprint of the nuclear fuel cycle. [5]
- Finally, uranium demand from the United States combined with demands from around the world (as other nations also expand their nuclear energy programs or new ones start) do not necessarily result in a shortage of uranium within this century as the amount of known resources will continue to grow as uranium prospecting continues in earnest as it has since around 2007. However, it is likely that the increased uranium demand will drive up the price of uranium; the final impact is unknown at this time. Furthermore, the United States currently has additional uranium resources in the form of more than 750,000 MTHM of depleted uranium tailings, the waste product from the enrichment of the LWR fuels. Although currently a liability that will need to be processed and placed in the geological disposal facility, this material could equally be used as the major component of the fuel to be loaded along with the fissile material such as U-235 or Pu-239 in future fast reactor systems.

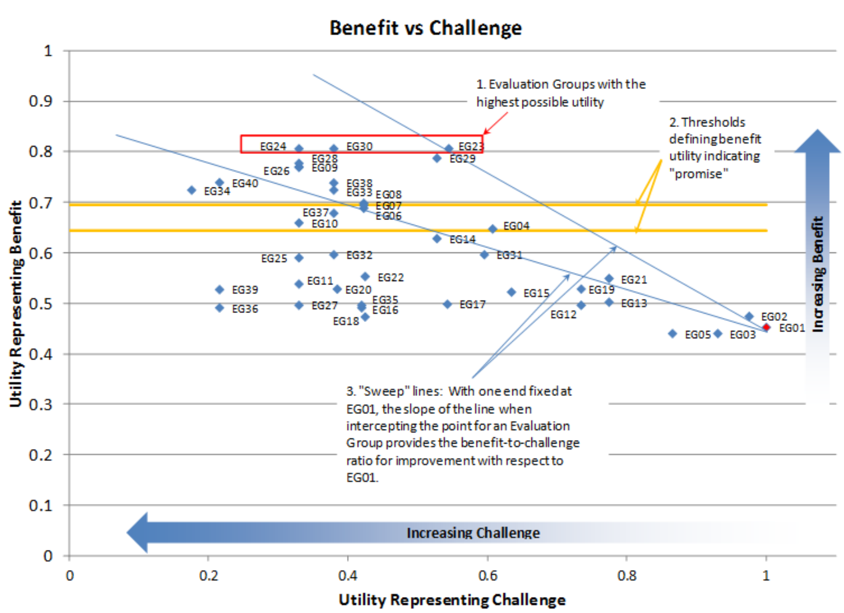

FIG. 2: An Example of the Benefit versus Challenge Results and the Methods Used for Identifying the Promising Options [2]

MSR: a unique reactor system

Liquid fueled molten salt reactors (MSR) have the advantage, though challenging at times, to perform on-line or off-line processing of the irradiated fuel salt depending on the design of the reactor. The process diagram for a U-Pu fuel cycle MSR (fast spectrum) should include the following key elements according to References 7, and 8:

- Removal of the gaseous and volatile fission products such as Xe/Kr, Iodine, tritium using various sorbents such as metal organic framework, silver loaded zeolite, caustic scrubbing, etc.
- Recovery and recycling of fissionable nuclides such as U and Pu
- Isolation of rare earth elements and other fission products
- Regeneration of the carrier salt with concurrent fuel composition adjustment
- Immobilization and disposal of fission products

In the United States, MSRs have advantageous technical characteristics to accomplish key objectives set out in the Executive Order (EO) of May 23, 2025, on "Reinvigorating the Nuclear Industrial Base" [9] which are:

- support the management of spent nuclear fuel and high-level waste and the development and deployment of advanced fuel cycle capabilities to establish a safe, secure, and sustainable long-term fuel cycle
- expand domestic uranium conversion capacity and expand enrichment capabilities sufficient to meet projected civilian and defense reactor needs for low enriched uranium (LEU), high enriched uranium (HEU) and high assay, low enriched uranium (HALEU)
- dispose of surplus plutonium through processing and making it available to industry in a form that can be utilized for the fabrication of fuel for advanced nuclear technologies

2. CONCLUSION

Nuclear strategic development is key to any long-term success of industrial innovation. Important decisions, which must be made on mid-development, are typically based on current external drivers like political, economic or technical boundary conditions. The universal vision for energy production is characterized by minimal use of natural resources and minimized production of waste, while being economically affordable and safe, secure and reliable in operation. MSR systems should be part of the strategy as fast-spectrum MSRs can be highly efficient heavy actinide burners. Secondly, both fast and thermal spectrum MSRs readily accept almost any fissile material as fuel. Finally, MSRs do not require creation of expensive fuel fabrication facilities or modification of existing plants to handle higher radioactivity fresh fuel.

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