LEU+ to HALEU Transitions in Advanced Reactor Fuel Cycles

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INTRODUCTION

In 2020, a high-assay low-enriched uranium (HALEU) workshop report led by Monica Regalbuto [1] highlighted the unique regulatory challenges of establishing a HALEU fuel cycle in the United States of America (USA). It noted that part of enriching HALEU is first to produce low-enriched uranium plus (LEU+), defined as between 5% and 10% ^{235}U enrichment. The report notes that LEU+ facilities would fall under a similar category of regulations as our existing low enriched uranium (LEU) fuel cycle, allowing existing enrichment servicers to leverage their experience and infrastructure before taking on the increased regulatory burden of producing HALEU. If a reactor could be redesigned to accommodate it, using LEU+ could delay the demand for HALEU.

In this work, we use Cyclus to model the nuclear fuel cycle (NFC) of a fuel cycle that deploys Westinghouse AP1000s, X-Energy Xe-100 (Xe-100), and Ultra Safe Nuclear Corporation (USNC) Micro Modular Reactor (MMR). After 10 years of operation with LEU+ fuel, the Xe-100 reactors transition to HALEU and new MMRs are fueled with HALEU. We will evaluate the impact of this transition on the delayed separative work units (SWU) and mass of HALEU required to meet various demand growth scenarios.

CYCLUS

Cyclus [2] is an agent-based NFC simulator that is versatile, open-source, and modular. The software achieves this versatility through a series of generic archetypes, which represent facilities or processes. Many standard fuel cycle facilities have been implemented in the Cycamore repository [3], which holds technology-agnostic archetypes for material sources, material sinks, enrichment services, separations capabilities, storage services, and a generic reactor. Outside of Cycamore, the community has created a catalog of archetypes that can simulate a wide range of fuel cycle activities (e.g., material diversion PYRE [4] or fuel burnup with OpenMCyclus [5]).

SCENARIOS

We will deploy reactors to meet energy demands drawn from U.S. Energy Information Administration (EIA) [6] and U.S. Department of Energy (DOE) projections [7], shown in Table I. The low growth scenarios correspond to 5%, 10%, and 15% increases in energy demand by 2050, and the high growth scenarios correspond to a doubling and a tripling of nuclear energy by 2050.

In Table II, we describe the three schemes we used to deploy reactors to meet the energy demand. Through the greedy scheme, we are not attempting to capture the complexity of the problem but rather to explore the implications of deploying a minimal number of reactors to meet the demand. Contrasty, the random scheme is a proxy for the complexity of the real-world deployment problem; however, it does not include the nuance of how individual deployments meet an end user's needs, which will drive the strategic decisions that utilities and ratepayers behind the meter make in their reactor choices. Combining the random and greedy schemes allows us to inject some uncertainty around which reactor will be deployed at any given time while ensuring meeting the demand efficiently.

TABLE I. Demand Growth Scenarios

Demand Growth	**Year-to-Year Increase**	**Source**
No Growth	0%	N/A
Low Growth	0.17%	[6]
	0.5%	[6]
	1%	[6]
High Growth	3.5%	[7]
	5.6%	[7]

TABLE II. Deployment Schemes

Scheme	Description
Greedy Deployment	Deploy the largest reactor first at each time step, fill in the remaining capacity with the next smallest, and so on.
Random Deployment	Use the date and hour as a seed to sample the reactor list randomly.
Initially Random, Greedy Deployment	Randomly deploy reactors until a reactor bigger than the remaining capacity is proposed for each time step, then fill the remaining capacity with the greedy algorithm.

ACKNOWLEDGMENTS

This research was performed, in part, using funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Program (Project 23-29656 DE-NE0009390) 'Illuminating Emerging Supply Chain and Waste Management Challenges'.

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