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Transitioning nuclear fuel cycles with uncertain fast reactor costs

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ABSTRACT

This paper applies a novel decision making methodology to a case study involving choices leading to the transition from the current once-through light water reactor fuel cycle to one relying on continuous recycle of plutonium and minor actinides in fast reactors in the face of uncertain fast reactor capital costs. Unique to this work is a multi-stage treatment of a range of plausible trajectories for the evolution of fast reactor capital costs over time, characterized by first-of-a-kind penalties as well as time- and unit-based learning. The methodology explicitly incorporates uncertainties in key parameters into the decision-making process by constructing a stochastic model and embedding uncertainties as bifurcations in the decision tree. "Hedging" strategies are found by applying a choice criterion to select courses of action which mitigate "regrets". These regrets are calculated by evaluating the performance of all possible transition strategies for every feasible outcome of the uncertain parameter. The hedging strategies are those that preserve the most flexibility for adjusting the fuel cycle strategy in response to new information as uncertainties are resolved.

1. Introduction

Time-dependent analyses of the nuclear economy, for instance to assess transitions between nuclear fuel cycles, often confront uncertainties by implementing a scenario-based approach in which uncertain variables are parametrically varied. However, large uncertainties in the cost, performance, and even availability of technologies associated with advanced nuclear fuel cycles are present and will likely remain unresolved for decades (Shropshire et al., 2009). Due to these uncertainties, a single optimal strategy for transitioning from one nuclear fuel cycle to another does not exist. Strong transition strategies should be flexible, enabling reasonable outcomes to be attained once these uncertainties are resolved.

This work applies a novel methodology, originally presented in (Phathanapirom and Schneider, 2015), to a case study involving transition from the current once-through light water reactor (LWR) fuel cycle to one relying on continuous recycle of plutonium and minor actinides in fast reactors (FRs) where the capital cost of FRs is uncertain and evolves through time. The methodology hinges on a decision tree analysis approach for incorporating uncertainties as future bifurcations in a single, coherent model, based on the principles of decision making under uncertainty. Unique to this article is a multi-stage treatment, including first-of-a-kind (FOAK) penalties, of plausible trajectories for the evolution of FR capital costs over time.

2. Background

Modern decision theory provides a systematic approach to choosing between alternative courses of action under conditions of imperfect knowledge, which may refer to either information or foresight. The work presented here deals with decision making under imperfect information, or uncertainty, where one or more decision-relevant parameters have many possible outcomes or end-states. This is termed the *no-data* decision problem, which consists of four components: (1) the available *actions* that can be taken, (2) the *states of nature* (or *end-states*) which may occur, (3) the *consequences* of each combination of action and state of nature (known as a *state-act pair*), and (4) a *choice criterion* by which the decision maker solves the final problem of choice.

Several techniques have been proposed to address the *no-data* problem (Gorenstin et al., 1993). Of these techniques, *scenario analysis* has been the most pervasive for handling uncertainty in the nuclear fuel cycle. The scenario approach finds an optimal plan for *N* possible scenarios, obtaining a set of *N* solutions. This approach assumes agents have perfect information about the state of nature that will prevail, and no systematic method is available for consolidating the plans to incorporate the uncertainties that are actually present. Instead, this work presents a methodology for handling uncertainties in the nuclear fuel cycle derived from concepts

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utilized in stochastic optimization. Here, uncertainties are explicitly embedded as future bifurcations with assigned probabilities within a single model. Using this model, a single strategy is found whose performance is optimal "on the average" for all scenarios.

The Dynamic Systems Analysis Report for Nuclear Fuel Recycle (DSARR) utilizes the scenario approach to examine systems costs, uranium resource impacts, and waste management impacts involved in transitioning fuel cycles from the current once-through (Dixon et al., 2008). The scenarios examined include once-through; single tier recycling in FRs only; and two tier recycling, first in LWRs, and then in FRs. One uncertainty considered by the DSARR report is the overnight capital cost of LWRs and FRs. The total cost of electricity is calculated for various values of these parameters and contrasted. Using a stochastic optimization approach, a hedging strategy (typically a partial closing of the fuel cycle, see (Phathanapirom and Schneider, 2015) would be chosen that allowed the greatest amount of flexibility until the uncertainty could be resolved. The strategy, using total cost of electricity as a metric, would minimize the additional costs accrued by following the hedging strategy compared with the costs if any feasible outcome for the uncertain parameter occurred. Then, a full closure of the fuel cycle, or abandonment of the transition, would occur, depending on the outcome of the LWR and FR capital costs.

3. Methodology

The transition scenario examined here is described and cast as a *no-data* decision problem in Section 3.1. Section 3.2 presents a methodology for selecting the optimal transition strategies under perfect information, as well as a general method, based on principles of stochastic programming, for selection of optimal hedging strategies. Section 3.3 briefly describes the Vegas fuel cycle simulator, the chosen analysis platform, and documents all input simulation data (Schneider and Phathanapirom, 2015).

3.1. Reference transition scenario

The scenario considered here involves transitioning from the current once-through LWR fuel cycle towards continuous recycle of plutonium and minor actinides in low conversion ratio FRs, depicted in Fig. 1. LWR uranium oxide (UOX) used fuel (UF) from existing LWRs is separated into fission products (FPs) for storage and subsequent disposal as HLW, uranium for reuse or storage, and transuranic (TRU) elements. TRU elements are then burned in FRs, producing electricity while achieving partial TRU destruction. FR UF is subsequently separated into the same three streams: U, FPs, and TRU. Separated TRU is then recycled and again burned in FRs. This closed fuel cycle utilizing FRs with a conversion ratio of 0.5 is aimed at minimizing the existing TRU inventory, similar to Evaluation Group 24 found in the Department of Energy's Fuel Cycle Options study (Wigeland et al., 2014). FR reprocessing capacity is assumed wholly adequate and may correspond to builds of co-located reprocessing and fuel fabrication facilities, demonstrated previously at the Idaho Integral Fast Reactor facility adjacent to EBR-II (Shropshire et al., 2009). Legacy LWR SNF[1] is assumed to go directly to disposal, and has no bearing on the decision made. This is consistent with current policy following a technical review by Oak Ridge National Laboratory.[2]

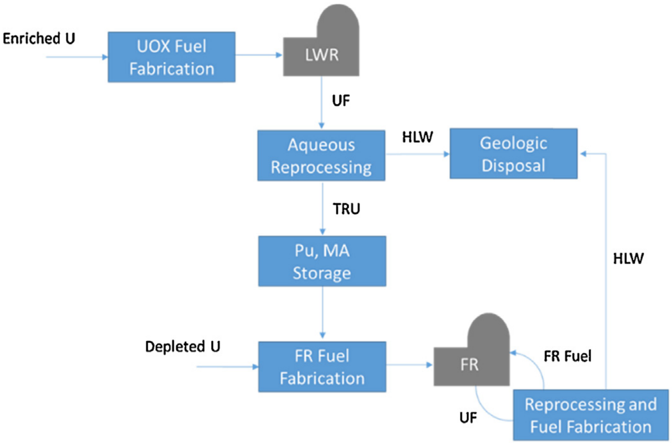

Fig. 1. Reference closed fuel cycle.

One key source of uncertainty regarding transition to the closed fuel cycle depicted in Fig. 1 is the capital cost of FRs. Given this uncertainty, the potential benefits of the transition are unclear. If FR costs are high relative to LWRs, the transition could be delayed or even abandoned at the expense of continued usage of natural resources and repository capacity. Alternatively, if FR costs are low relative to LWRs, it would likely be optimal to pursue an aggressive schedule for closing the fuel cycle.

Simulating transition strategies between once-through and continuous FR recycle while incorporating the uncertainty in FR capital costs gives rise to a *no-data* decision problem, depicted in Fig. 2. Table 1 accompanies Fig. 2 and provides a timeline of the information available to agents during each stage of the transition. The decision time period extends from 2015 to 2100, though simulations are run through 2160 (an additional lifetime of the longest operating facility) to ensure that liability costs are accounted for.[3] The possible FR capital cost end-states are given in Table 2. The lowest, medium, and highest end-states are taken from the low, nominal, and high estimates from the Advanced Fuel Cycle Cost Basis report (Shropshire et al., 2009) and represent engineering estimates. The low and high end-states are taken as equidistant between the medium and lowest, and medium and highest end-states respectively. A FOAK penalty is applied to the first 8 FRs built, according to the Cost Estimating Guidelines for Generation IV Nuclear Energy Systems (Economic Modeling Working Group, 2007). According to (Economic Modeling Working Group, 2007), direct construction costs are assumed to decline by 6 percent with each doubling of capacity due to "learning elasticity", up to 8 GWe of installed capacity.[4] For instance, a FOAK facility with direct construction costs of $1000 M can expect a decline to $940 M for the second facility. Averaged over the first 8 facilities, this equates to a FOAK penalty of approximately 8 percent over the *n*th-of-a-kind (NOAK) facility.

FR construction and operation can only go forward if a supply of separated TRU is available. As described further in Section 3.3, the fuel cycle simulation platform used for this study will only build FRs

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[1] Legacy SNF refers to U.S.-discharged used nuclear fuel as of 2011, see Wagner et al. (2012) for a description.

[2] Wagner et al. (2012) found that 98 percent of the total current inventory of commercial SNF may be disposed without the option for retrievability with no shortage of fuel for later reuse or research purposes under the assumption of 2000 tIHM/yr reprocessing capacity available beginning in 2030. While the recycle scenarios reviewed in this paper do not mirror that of (Wagner et al., 2012), the conclusion found in (Wagner et al., 2012) has been used as justification for current policy to directly dispose the existing inventory of SNF.

[3] Simulations are carried out through an additional lifetime of the longest operating facility to ensure liability costs are accounted for. For example, results from Vegas simulations in this study are analyzed for the time period [2015, 2100], but an actual simulation is carried through to 2160, assuming a reactor operating lifetime of 60 years. Otherwise, reactors may be built at the "end" of the period of interest despite a fuel shortage occurring in the future and fuel that would be reprocessed but only after the time period of interest would be treated by the LCOE calculation as being directly disposed.

[4] Economic Modeling Working Group (2007) assumes design and certification costs to be equally distributed over the first 8 GWe of capacity built. Here, the assumption is lifted and applied to simply the first 8 units built.