Economic Model Development for Deep Borehole Repositories

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INTRODUCTION

In order to be seen as a viable alternative to mined geologic disposal, deep borehole disposal must be 1) technologically achievable, 2) safe for normal and off--normal operations in surface and sub-surface environments, 3) suitable to a range of locations, 4) suitable to a variety of waste forms, and 5) economically competitive. Deep Isolation has devoted project efforts over the past several years to address each of these areas, and the results of the former areas all feed into the economic considerations of deep borehole disposal. Through a project funded by the Advanced Research Projects Agency – Energy (ARPA-E) Converting UNF[1] Radioisotopes Into Energy (CURIE) program, Deep Isolation is developing an economic model to assess the range of disposal costs for streams generated from pyroprocessing used light water reactor fuel. The project, *Highly Efficient Electrochemical Oxide Reduction for U/TRU Recovery from LWR[2] Fuel*, is led by Argonne National Laboratory (ANL) with support from Deep Isolation, Oklo Inc., and Case Western Reserve University, and inputs from each project partner will inform the economic model.

The project will progress an economic analysis through the framework of Fig. 1.

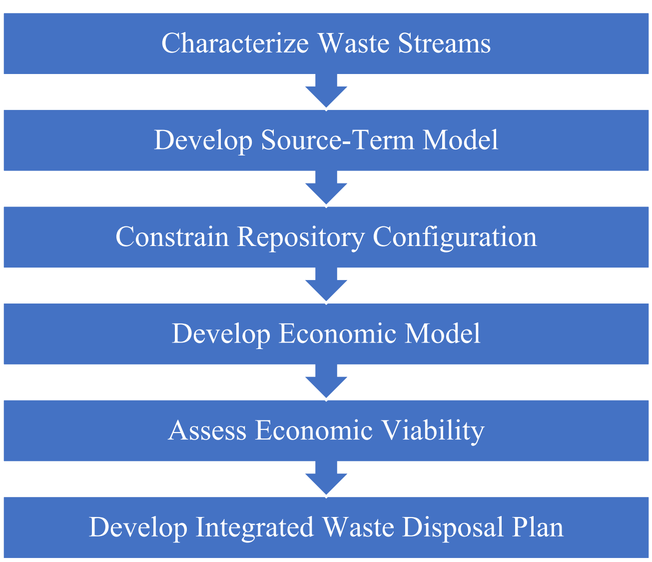

Fig. 1. Economic analysis workstream for ANL-led CURIE project

DESCRIPTION OF WORK

The project partners are gathering necessary information to characterize the chemical, structural, thermal, and radiological properties of the post-processing waste forms. This information will then be incorporated into a source-term model to determine initial activity of safety-relevant radioisotopes, release and degradation rates, and thermal outputs per unit volume of waste. Using the outputs of the source-term model, constraints such as minimum disposal depth to ensure acceptable long-term peak radiological dose (well below 0.1 mSv/yr), will be determined. With constraints identified, the economic model can be fully developed, and its outputs will be used to assess the economic viability for deep borehole disposal of post-processing waste streams (relative to a 0.1¢/kWh waste disposal cost metric) and a comprehensive waste disposal plan.

The economic model being developed sorts high-level cost areas into a work breakdown structure (WBS) akin to guidance from the European Joint Program on Radioactive Waste Management (EURAD). Deep Isolation selected the EURAD WBS based on previous work on international cost studies, which showed that the EURAD framework offers a detailed breakdown of economic considerations for geologic disposal in a standardized, multi-national framework. The EURAD Level 1 WBS is shown in Table I [1].

TABLE I. EURAD Work Breakdown Structure Summary

Level 1 Cost Area	**Notable Level 2 Topics**
Program Management	Project Management
Stakeholder Engagement	Community Compensation
Siting	Refined Site Evaluation
Site Investigations	Site Investigations
Monitoring	Operational Monitoring
Safety Assessment and Analyses	Safety Assessment
Design	Design
Other Actions/Documents	Security Plan and Costs
Construction	Drilling
Operation and Maintenance (O&M)	Disposal Canisters
Closure	Backfilling and Sealing
Institutional Control	Active Institutional Control

[1] Used nuclear fuel (UNF)

[2] Light-water reactor (LWR)

Within each Level 1 cost area are one to four Level 2 cost topics (including those mentioned in Table I), tailored to specifically address deep borehole disposal from existing EURAD general guidance. While the ultimate goal in cost modeling is a predictive, bottom-up driven model based on prototypic experience, some cost assumptions are currently informed from mined geologic and low-level waste repositories, as well as from the nuclear dry storage and transportation and drilling industries. Uncertainties in estimates are factored into both technological and project contingency levels (scaled 1 through 5 and 1 through 4, respectively) and each score is factored into a contingency budget through a methodology developed by the Electric Power Research Institute [2].

Each cost area is a function of one or more of these factors, described in subsequent sections:

- Inventory,
- Borehole Configuration,
- Location, and
- Timing.

Inventory

Deep Isolation, in collaboration with NAC International Inc. (NAC), University of California Berkeley, and Lawrence Berkeley National Laboratory, is developing a Universal Canister System (UCS) for advanced reactor waste streams through its ARPA-E UPWARDS[3] project. Initial studies of pyroprocessing operations indicate that the resultant waste streams could fit into any of the three UCS canister sizes, or classes. In the UCS Preliminary Design Report [3], NAC evaluated each canister class in normal and off-normal events and demonstrated satisfactory safety for storage and transportation per current regulatory requirements, and satisfactory safety for disposal based on existing and anticipated regulations. Though nearly identical in length, each class of canister differs in diameter and shell thickness to accommodate a range of potential waste streams. As such, each class differs in volumetric, weight, thermal, and radiological limits. These differences result in competing cost effects. An inventory loaded into the smallest UCS canisters will necessitate smaller diameter boreholes but will result in more canisters (and likely more boreholes). Conversely, loading waste into the largest canister will result in larger diameter boreholes, but will require fewer canisters (and likely fewer boreholes). Considering that canister costs and drilling costs (parts of O&M and Construction cost areas in the WBS, respectively) are consistently the two highest cost contributors in Deep Isolation's cost model, optimizing the techno-economic tradeoff for a specific waste inventory is a priority.

Deep Isolation is refining canister cost estimates through prototype fabrication trials and supply chain evaluations in ongoing projects over the next year. Prior to this work, however, Deep Isolation factored economies of scale into earlier versions of its economic model and cost assumptions. Initial results demonstrate that a client with a small waste inventory requiring only a few canisters would be subject to similar costs in fabrication setup and quality assurance as one with a large waste inventory requiring several thousand canisters. With these costs being distributed among the per unit canister costs, a client with a small inventory may result in a higher unit cost, particularly without canister fabrication synergies to minimize down time between welding or machining operations (though some of these scale inefficiencies may diminish as the canister design and processes become refined for manufacturing).

Borehole Configuration

In addition to varying borehole diameters, Deep Isolation considers different lengths and orientations to identify the optimum repository configuration for a particular inventory, site, and geology. Preliminary calculations demonstrate long-term safety for spent nuclear fuel disposal utilizing a reference borehole architecture at 1 km depth [4], [5], though Deep Isolation has conservatively assumed a disposal depth of 1.5 km in previous cost studies. In a 1.5 km case, a vertical borehole would need to reach a depth of 3 km to have a 1.5-km long disposal zone[4]. At such depths, vertical boreholes will often require drilling through extensive lengths of crystalline basement rock, increasing the difficulty and associated costs of drilling, and thus counteracting perceived savings from a conceptually simple (relative to directional drilling) approach. Vertical borehole configurations can be optimized through sensitivity studies of disposal zone length, minimum disposal depth, and specific geology, but have thus far been shown to generally be more expensive than horizontal boreholes. In previous cost studies, horizontal boreholes were assumed to include a 1.5-km deep vertical portion followed by about 0.5 km of a curved directional portion before reaching 1.5 km of horizontal disposal zone. Horizontal boreholes are generally assumed to be drilled in sedimentary formations, but directional drilling in other geologies is feasible[5]. In this project, Deep Isolation will evaluate the effects on cost of varying disposal depths of horizontal and vertical boreholes between 1 km and 2 km.

[3] Universal Performance Criteria and Canister for Advanced Reactor Waste Form Acceptance in Borehole and Mined Repositories Considering Design Safety (UPWARDS)

[4] The preliminary design of the UCS limits the maximum disposal depth to 2 km, though future design iterations are likely to increase the disposal depth, as needed.

[5] Horizontal boreholes of Deep Isolation's model have been shown feasible to accommodate all but the largest (Class 3) UCS canister. Further study will be needed before horizontal boreholes for Class 3 canisters can be pursued.

Location

Though local geology can influence the cost and likelihood of disposal at a particular site, Deep Isolation has sufficiently flexible site screening criteria [6] to avoid costly over-reliance on a particular site (barring sociopolitical factors). This flexibility can enable opportunities to find locations with lower land costs, suitable local labor and manufacturing supply chain, proximity to drilling infrastructure, existing site investigation work, and an informed and consenting local community. Many of these opportunities may be realized through co-location of a borehole repository with the waste generating site (i.e., reactor or processing facility). Co-location is an option in the economic model, which enables savings in O&M (specifically in waste transportation costs), site investigations, other actions/documents (specifically in security and road infrastructure costs), and program management, though additional savings may eventually be included as model development efforts progress.

Timing

Though the largest cost areas are O&M and Construction, and their timing is generally driven by inventory size, other cost areas may vary in significance as a function of timing. In particular, stakeholder engagement, monitoring, and institutional control have duration-driven costs which are largely independent of inventory. Generally, these durations stem from regulatory or otherwise prescribed timing. For instance, requirements for a retrievability period (e.g., up to 50 years) will prompt longer monitoring and security durations, resulting in higher costs. Such cases, depending on their severity, may prompt cost changes in inventory-driven areas, as well. Specifically, requirements for a retrievability period beyond the design life of the canister may require additional analyses and a more robust canister design and borehole system. These ripple effects are not yet reflected in the model but have been foreseen and discussed by Deep Isolation in the UPWARDS project [7]. Ultimately, Deep Isolation will conduct sensitivity studies on the influence of timing on disposal cost.

Notable Differences

While the framework and four key factors discussed above are likely to remain similar for the economic model in the CURIE project, it is worth noting that the latest Deep Isolation cost model is based upon disposal of LWR fuel assemblies, not pyroprocessing waste. As such, logistical differences could have an impact on cost. Most notably, LWR fuel assemblies have generally been assumed to be loaded into the UCS vertically in a water pool setting. The latest model does account for some of the inventory needing to be packaged in a hot cell, possibly in a horizontal orientation; however, the pyroprocessing waste forms may require additional loading considerations such as an internal canister, which may result in packaging cost differences. These logistical differences may also necessitate additional or substitutional infrastructure and location requirements, which could provide previously unaccounted constraints and/or costs to the model. The extent to which such parameters are consequential and incorporated into the model will be discussed in later economic workstream outputs from Fig. 1.

RESULTS

A new cost model with greater fidelity in terms of cost factors and uncertainty analysis is being developed for assessing the economics of disposing pyroprocessing wastes in deep boreholes. The model has flexibility to accommodate multiple configurations of deep borehole repositories, including horizontal boreholes in sedimentary rock and vertical boreholes in crystalline rock, as well as variations in borehole diameter to accommodate different classes of the UCS canister. Some of these concepts were compared in the latest iteration of the cost model assuming a single commercial pressurized water reactor's spent fuel inventory, as summarized in Table II.

TABLE II. High-Level Findings from Cost Comparisons

Concept	Relative to…	Savings
Borehole Disposal	Mined Repository	33-56%
Horizontal Borehole	Vertical Borehole	20%
Earliest Possible Disposal	Standard Timing (26 years slower)	13%
Co-Located Borehole Site	Generic Borehole Site	4%

Though numerical results of borehole disposal costs in the CURIE project will not be finalized until 2025, Deep Isolation has confidence from previous studies (as evidenced by Table II above) that disposal costs (including contingency) will not impede development of commercial pyroprocessing of spent nuclear fuel. In addition to high-level radioactive waste (HLW), Deep Isolation is also investigating any cost effectiveness of disposing Greater-Than-Class C and other low-level wastes generated by pyroprocessing in otherwise unused portions of the boreholes.

CONCLUSION

The ANL-led CURIE project allows the opportunity to determine the technical, safety, and economic viability of not only pyroprocessing UNF for future use but also of the disposal of waste streams from pyroprocessing. It is expected that the results of this project will enable the use case for a domestically available nuclear fuel source for advanced reactors with a viable disposal pathway for its processing waste products. From an economic modeling standpoint, this project presents an early opportunity to expand the use of

Deep Isolation's model from primarily LWR fuel assemblies to also include processed HLW.

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