Integrated Systems Analysis for a Regional Deep Borehole Repository for Commercial Spent Nuclear Fuel – 16291

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ABSTRACT

Some nuclear waste stakeholders have suggested private interim storage facilities (ISF), but little work has been done to consider the cost or logistics for nuclear waste management or disposal facilities smaller than the national scale. This paper performs an integrated system analysis for a deep borehole repository system which would accept waste from a regional subset of the national commercial reactor fleet. The regional subset is comprised of a centrally-located host state with a large SNF inventory surrounded by states with small SNF inventories. The chosen region will contain between one-fifth and one-quarter of the national commercial SNF inventory. Using best estimates of past and future SNF discharges in the sample region, the SNF inventory in the chosen region is characterized by reactor of origin. Basic parameters are then chosen for the regional repository, such as the annual rate of waste emplacement and the time necessary to process borehole-specific waste canisters. Scenarios chosen for analysis test the sensitivity of a variety of system parameters, including the annual rate of waste acceptance, the division of annual waste acceptance among sites, the use of bare fuel transportation canisters, and the size of the regional subset of reactors. Estimated costs for the facility are $13 billion for around 27,000 MT of SNF and $16 billion for around 35,000 MT. This translates to $490,000 per MT and $466,000 per MT, respectively. These unit costs are comparable to the $370,000 per MT estimate for the full 140,000 MT national inventory.

INTRODUCTION

A consent-based siting process, recommended by the Blue Ribbon Commission on America's Nuclear Future for the siting of new nuclear waste management facilities, could give rise to high-level nuclear waste repositories of many designs and sizes. While previous efforts in the United States focused on three geologic environments, vitrified volcanic tuff and ignimbrite, salt rock, and basalt, research programs worldwide have also focused on disposal in crystalline rock, fine-grained sedimentary rocks, clay and shale, and deep boreholes. By expanding the list of candidate designs, a larger number of communities may participate in a future siting process. A repository could limit the acceptance of waste to a regional subset of the national fleet or accept waste on a contractual basis from individual utilities or power plants, creating new scenarios for logistical and economic analysis. In addition to spent nuclear fuel (SNF), a repository could also accept a variety of defense wastes, including cesium and strontium capsules from Hanford as recently proposed by the DOE. One of these possible scenarios, a regional deep borehole repository in the Midwestern United States, is considered in this paper. This paper performs an integrated system analysis for a regional deep borehole disposal (DBD) repository shared by Illinois and its surrounding states. A waste handling and canister loading facility, co-located with the repository, would accept fuel transported from reactor sites and perform handling operations. This paper describes and discusses the regional SNF inventory, DBD facility characteristics, throughput, and acceptance strategies which serve as inputs for the fuel logistics and cost simulator TSL-CALVIN. CALVIN analyzes various proposed iterations of a nationwide SNF acceptance program and calculates a range of system metrics including utility dry storage costs, fuel handling costs, and a transportation shipping schedule for use in CALVIN's sister program TSL-TOM. TOM calculates the number and costs of assets that would be required for different strategies and the cost of operating the transportation system. Results analyzed include rough economic estimates for facility costs and equipment requirements, culminating in a unit cost per metric ton for a regional deep borehole repository.

MODEL INPUTS

CALVIN's database and input parameters must be adapted to the regional subset. This section will discuss the necessary adjustments, including identifying and estimating the SNF inventory at reactors in the proposed region, parameters for a DBD facility, transportation rates, and acceptance priority. A list of scenarios at the end of this section will summarize the regional cases tested.

Defining the Midwest Region and SNF Inventory

The state of Illinois has more than ten percent of the current inventory of commercial spent nuclear fuel (SNF) in the United States. Roughly 9000 metric tons (MT) of SNF is at 11 operating reactors on six sites, two closed reactors, and a wet interim storage facility (ISF) located at a former reprocessing plant near Morris, IL. Four states that border Illinois have smaller nuclear fleets. Iowa and Missouri only have one operating reactor each, Wisconsin has two, and Michigan has four. There are also several closed or decommissioned reactors with waste on site in Illinois and surrounding states. The total estimated SNF discharge from the chosen states, around 27,000 MT, would be larger than planned repositories in Sweden and Finland. In short, the SNF burden shared by these states could be large enough to justify a regional repository. This group of states (Wisconsin, Iowa, Missouri, Michigan, and Illinois) will be referred to as the "Midwestern Region" or "MR." To compare the Midwestern Region to other options, two other groupings will be considered. These groupings are the "Midwestern Region Plus" and the entire United States (as considered in other work by ANL). The Midwestern Region Plus, or "MR+," will include all of the fuel from the MR and fuel from an additional set of reactors in nearby states, including Wolf Creek, KS, Cooper and Fort Calhoun, NE, Arkansas Nuclear One, AR, and Monticello and Prairie Island, MN. If all operating reactors finish their sixty-year lifetimes, the MR+ region will contain 35,000MT of SNF. Cooper and Monticello already have considerable inventory in interim wet storage Morris, IL facility, simplifying the division of responsibility for that site.

The existing SNF inventory by state can be found in a 2012 Congressional Research Service paper by James Werner, current through the end of 2011 [2]. The five states in the proposed Midwest Region (IL, WI, MI, MO, and IA) contain around twenty percent of the nation's SNF, while the larger MR+ contains about twenty-five percent of the national inventory. The totals by state are listed in Table I.

TABLE I. 2011 SNF Inventory, Selected States, from Werner [2]

State	**Inventory (MT) in 2011**	**State**	**Inventory (MT) in 2011**
Iowa	476		
Illinois	8,691	Arkansas	1,333
Michigan	2560	Kansas	646
Missouri	679	Minnesota	1,203
Wisconsin	1,334	Nebraska	853
MR Total	**13,740**	**MR+ Total**	**17,775**

Inventories by reactor site were published in a 1995 Energy Information Administration report, current through 1995 [3]. With the exception of a small number of assemblies at Palisades, all assemblies remained in wet storage. CALVIN's database contains an approximation of dry storage inventory by reactor at the beginning of waste acceptance in 2030 is shown in Table II. One major allocation strategy is to remove enough fuel from each reactor's pool storage each year to prevent the use of additional dry casks.

TABLE II. Approximate Dry Storage Inventory in 2030 [4]

Reactor	**2030 Dry Inventory (MT)**	**Reactor**	**2030 Dry Inventory (MT)**
ANO	1,348		
Big Rock Point	58	Kewaunee	517
Braidwood	853	LaCrosse	38
Byron	962	LaSalle	1,041
Callaway	227	Monticello	309
Clinton	452	Palisades	684
Cooper	353	Point Beach	759
DC Cook	930	Prairie Island	837
Dresden	1,388	Quad Cities	1,319
Duane Arnold	453	Wolf Creek	30
Fermi	292	Zion	1,019
Fort Calhoun	255	**Total**	**14,124**

The future of nuclear power in the United States is uncertain over both the short and long terms, ranging from premature closure of many reactors in the fleet to the replacement or expansion of existing generation capacity with time. The middle case treated here sees existing reactors finish their sixty-year lifetimes. If each reactor currently operating finishes its sixty-year operating lifetime, the total SNF will be around 27,000 MT in the MR and around 35,000 MT in the MR+. An approximate breakdown by reactor is shown in Table III.

TABLE III. Estimated SNF Inventories for Selected Locations at End-of-Life

Plant	Estimated Inventory (MT)	Plant	Estimated Inventory (MT)
ANO	2,429		
Big Rock Point	58	Morris	674
Braidwood	2,875	Kewaunee	517
Byron	2,904	LaCrosse	38
Callaway	1,643	LaSalle	3,227
Clinton	1,570	Monticello	693
DC Cook	2,893	Palisades	1,068
Cooper	866	Point Beach	1,422
Dresden	2,451	Prairie Island	1,437
Duane Arnold	946	Quad Cities	2,729
Fermi	1,349	Wolf Creek	1,541
Fort Calhoun	681	Zion	1,019
MR Total	**27,384**	**MR+ Total**	**35,032**

Borehole Repository Description

Deep boreholes were first considered during early waste disposal research by the US National Academy of Sciences. The current concept for a deep borehole repository stems from work in the 1970s and 1980s by the Office of Nuclear Waste Isolation (ONWI), the national research program that laid the groundwork for many nuclear waste disposal concepts. The capstone report for the deep borehole design was produced by Woodward-Clyde Consultants [5], and many elements of this design have been preserved in recent work at Sandia National Laboratory (SNL), the University of Sheffield, Sweden’s disposal organization SKB, and MIT. SNL produced an updated reference design for the deep borehole concept [6], adapting Woodward-Clyde’s design to account for modernized drilling practices and new economic realities. SNL’s design, excluding the consolidation of fuel assemblies, serves as the basis for the economic estimates presented in a later section. SNL’s reference design is a 4-5km vertical borehole with at least the bottom 2km in crystalline basement rock (granite), cased throughout during emplacement. Waste is emplaced in the bottom 2km of the well. The internal diameter of the disposal region is large enough to accommodate a canister containing a single PWR assembly or a denser configuration of consolidated fuel rods of approximately the same size. Each borehole contains around 400 canisters, stacked vertically, equivalent to 253 MT in the consolidated case or 160 MT of unconsolidated SNF assemblies. The base case presented here will choose to dispose of assemblies in their un-altered configuration, so the standard borehole will contain 160 MT of SNF. The SNL design work estimated a total cost per borehole of $40 million (2011$) and a completion time of six months. The $40 million estimate includes all borehole-related operations, including the consolidation of SNF and the cost of canisters. As a result, this estimate may be slightly higher than the estimate for the base case. For BWR assemblies, a triangularly-packed canister would have a similar diameter to the PWR assembly, likely contributing some extra cost for a marginally wider borehole diameter. Based on SNL's estimates, a single drilling rig could make space for 320 MT of unconsolidated SNF per year, meaning that all other parts of the facility must process around 27 MT per month per drilling rig. SNF will arrive on-site in dual-purpose canisters or bare fuel canisters (depending on scenario) and spend a small amount of time on a lag storage pad prior to repacking into borehole-specific canisters. The transportation schedule has been chosen such that the annual rate of fuel transportation is equal to the annual rate of disposal, eliminating the need for a true interim storage or SNF aging facility.

The canister design will have an outside diameter of 32cm for the PWR case and 37cm for the BWR case. These canisters will be adequate for all SNF assemblies in the region, with the exception of BWR fuel from LaCrosse and Big Rock Point, which is too large to fit in the proposed BWR canister in the triple-packed configuration. An independent analysis of SNL's cost-per-canister estimate [5] yielded similar results. The estimated cost per canister fabrication, loading, and completion is $16,700, which translates to $6.7 million per borehole or $42,000 per MT of fuel.

Transportation and Logistics Parameters

The transportation parameters required for analysis by CALVIN vary depending on the case. These variations include the size of the region (MR vs. MR+ vs. national), the order in which fuel is queued for transportation to the repository (termed "acceptance priority"), the annual rate of fuel transportation and disposal, and whether or not re-usable bare fuel canisters are permitted for reactor-to-repository transportation. Acceptance priority can be determined via many factors, but the most successful (and, perhaps, most politically attractive) strategies prioritize the removal of SNF from decommissioned reactors first. This "stranded fuel" can be transported to the repository within the first several years of operation. After stranded fuel is dealt with, the acceptance priority transitions to operating reactors. The most economic strategy attempts to prevent additional dry casks from being loaded by accepting spent fuel directly from the SNF pool, although lower rates of annual disposal cannot completely prevent the use of additional dry casks. CALVIN's default setting removes the oldest spent fuel first. A more detailed analysis could consider the relative benefits of mixing old and freshly-discharged SNF to balance heat loads. Additionally, the transportation of damaged fuel assemblies and their treatment between reactor and disposal must be explored in more detail in future work. The annual fuel acceptance and disposal rate of the facility ranges from 500MT/year to 1,750MT/year depending on the case. When possible, each acceptance rate and chosen region was analyzed with and without the use of bare fuel canisters. The scenarios tested are listed below in Table IV. Cases marked DS-SD only remove fuel from reactor sites after the reactor has shut down.

TABLE IV. Scenario Numbers With Description

Scenario Number	Scenario Description
2053	DBD-1 MR Cans only at 500MT/year
2054	DBD-2 MR Cans only at 750MT/year
2055	DBD-3 MR Cans only at 1000MT/year
2056	DBD-4 MR Cans only at 1250MT/year
2057	DBD-5 MR Cans only at 1500MT/year
2058	DBD-6 MR Cans and Bare at 500MT/year
2059	DBD-7 MR Cans and Bare at 750MT/year
2060	DBD-8 MR Cans and Bare at 1000MT/year
2061	DBD-9 MR Cans and Bare at 1250MT/year
2062	DBD-10 MR Cans and Bare at 1500MT/year
2063	DBD-11 MR Cans only at 1000MT/year DS-SD
2064	DBD-12 MR+ Cans only at 1000MT/year
2065	DBD-13 MR+ Cans only at 1000MT/year
2066	DBD-14 MR+ Cans only at 1500MT/year
2067	DBD-15 MR+ Cans only at 1750MT/year
2068	DBD-16 MR+ Cans and Bare at 1500MT/year
2069	DBD-17 MR+ Cans and Bare at 1500MT/year DS-SD
2000 (Base)	FY15 Base Case (140,000 MT) for National Inventory

RESULTS

Once the inputs are set, the scenarios listed in the previous section were run with CALVIN and TOM. Table V summarizes the cost per MT of fuel for each of the scenarios. In order to be compared to the national base case, costs include utility costs, transportation costs, and canister costs, but not disposal costs (as these are not comparable between cases).

TABLE V. Summary of Results for Different Transportation Cases With Explanation

Scenario Number	Scenario Description	Utility + Transport+ Canister Loading	Cost / MT
2000 (Base)	FY15 Base Case (140,000 MT)	$52,000,000,000	$371,528
2068	DBD-16 MR+ Cans and Bare at 1500MT/year	$16,324,907,555	$465,097
2066	DBD-14 MR+ Cans only at 1500MT/year	$16,595,057,031	$472,794
2067	DBD-15 MR+ Cans only at 1750MT/year	$16,690,987,953	$475,527
2062	DBD-10 MR Cans and Bare at 1500MT/year	$13,230,169,236	$484,622
2061	DBD-9 MR Cans and Bare at 1250MT/year	$13,458,196,699	$492,974
2057	DBD-5 MR Cans only at 1500MT/year	$13,721,803,009	$502,630
2056	DBD-4 MR Cans only at 1250MT/year	$13,910,315,276	$509,535
2060	DBD-8 MR Cans and Bare at 1000MT/year	$14,013,067,276	$513,299
2065	DBD-13 MR+ Cans only at 1000MT/year	$18,037,144,277	$513,879
2069	DBD-17 MR+ Cans and Bare at 1500MT/year DS-SD	$18,310,778,488	$521,675
2063	DBD-11 MR Cans only at 1000MT/year DS-SD	$14,248,944,953	$521,939
2064	DBD-12 MR+ Cans only at 1000MT/year	$18,459,323,162	$525,907
2055	DBD-3 MR Cans only at 1000MT/year	$14,650,785,029	$536,659
2059	DBD-7 MR Cans and Bare at 750MT/year	$15,536,191,952	$569,091
2054	DBD-2 MR Cans only at 750MT/year	$16,147,050,822	$591,467
2058	DBD-6 MR Cans and Bare at 500MT/year	$19,158,732,561	$701,785
2053	DBD-1 MR Cans only at 500MT/year	$19,617,885,923	$718,604

To complete the full economic analysis, it is necessary to estimate the cost of the deep borehole system for the disposal of SNF. The more recent estimates for this design come from SNL, specifically Arnold et al. [7]. Borehole construction, emplacement, and completion costs are estimated at $213,921 per MT of fuel in the case, adapted for the case of unconsolidated fuel. These estimates are summarized in Table VI.

TABLE VI. Cost Estimates per Borehole from Arnold et al. [7] in 2014$

Expense	Cost	Cost / MT[a]
Construction	$28,728,166	$179,551
Emplacement	$2,920,536	$18,253
Sealing	$2,578,645	$16,117
Total	$34,227,346	$213,921

[a]Adapted for 160 MT boreholes for assembly disposal.

Table VII shows the full repository system cost estimate (from utility costs to repository closure), proposed repository capacity, and cost per MT.

TABLE VII. Cost Comparison Between Yucca Mountain [8] and DBD Cases

	Repository System Cost (2014$)[a]	Capacity	$ / MT
MR DBD	$18,900,810,149	27,300 MT	$692,337
MR+ DBD	$21,245,731,585	35,100 MT	$605,291
Yucca Mountain	$106,608,883,072	140,000 MT	$761,492

[a]Includes $5 billion expense for borehole site characterization

Finally, Table VII shows comparative unit costs for the two regional deep borehole cases and the FY15 averages performed for the entire nation using CALVIN. As the scenarios presented for the DBD cases are somewhat idealized, they are actually more comparable to the bottom quartile of the national fleet cases and this is reflected below.

TABLE VIII. Pre-repository Cost Comparison Between TSL-CALVIN-based Analysis for National and Regional Reactor Fleets in 2014 dollars

	$ / MT
Regional Average	$536,323
MR Average	$558,419
MR+ Average	$495,813
FY15 Average	$476,124
FY15 Bottom Quartile	$415,922

DICUSSION OF RESULTS

The lowest-cost cases are those that allowed transportation in bare fuel canisters, which was an expected result also seen in the national analysis. The conventional wisdom of economies of scale holds true in that the larger MR+ region had a cheaper unit cost (7% difference) than the MR region, but this was not the case for annual acceptance rates. Each region has an optimal annual transportation rate (1,500MT/year for the MR+ case), and going over this annual rate actually increases costs. Transportation rates above the optimal level do not re-use transportation canisters as many times as lower rates, while rates below optimal do not remove fuel from reactors quickly enough and suffer from larger utility-side storage costs. The target facility completion time of 25 years (i.e. 1,500MT/year) was cheaper than the original cost of 30 years (1,000MT/year). Location of the repository was moved by 140 miles north to test the cost sensitivity of the chosen location in Central Illinois, but the average costs per MT were indistinguishable for all cases.

Using the same methods as the plethora of national cases calculated each year, the regional DBD approach proposed here was found to be more expensive than the national fleet, but not dramatically larger. The approximately 25% difference between the national case's bottom quartile and the better cases for the regional approach is small enough that this approach could be considered on its other merits, potentially providing a more palatable political solution or faster implementation. The cost differences shown in Table VII which appear favorable to DBD in comparison to Yucca Mountain are likely a result in cost inflation in the 2008 TSLCC for Yucca Mountain [8] as compared to the relatively unproven estimates found in SNL's 2011 paper [7]. The borehole case also has the benefit of a pay-as-you-go organization, which means that fuel can be disposed as it is received and that the facility is constructed incrementally. In practice, this eliminates the need for a large ISF and offers some cost savings in that area. However, if an ISF were sited outside of the Midwest and a large amount of fuel was removed from the region, it would likely increase transportation costs enough to make a regional repository a financially unattractive option.

CONCLUSION

The integrated systems analysis presented in this paper is meant to provide preliminary logistics and cost estimates for a regional deep borehole repository in the Midwestern United States. This paper used the same programs (TSL-CALVIN and TSL-TOM), databases, and methodology as the broader national interim storage and repository program with borehole-specific additions. CALVIN estimates dry cask costs and costs at the ISF and MGR, and TOM takes scheduling information from CALVIN to estimate transportation system costs. With an estimated pre-repository cost of $500,000 per MT in selected ("best") cases, a regional borehole repository would be roughly 25% more expensive than a national case, owing to the smaller scale and less re-use of transportation equipment and handling facilities. Deep borehole disposal is, on paper, cheaper than the mined repository option, so a regional deep borehole repository would reach competitiveness with the national project partially on the basis of repository choice. Even if the regional repository option is economical, however, political questions remain. As with many other alternative repository ideas, federal laws must be amended to allow for options outside of the Yucca Mountain repository. The regional facility in theory sacrifices some efficiency for political feasibility and simplicity in transportation, as only one state which is not a stakeholder in the MR and MR+ cases will have fuel transported through the state. The assumption that a state and local communities already favorable to nuclear power will be favorable to a consent-based siting process may not hold up, although this connection holds true elsewhere in the world. Another political issue would be the ownership of fuel at the GE Morris ISFSI, as two reactors outside of the compact (San Onofre 1 and Haddam Neck) have fuel in storage there.

Future work can focus on logical expansions of this concept. This could include applying the regional storage approach to other regions or proposing utility-driven approaches in which larger nuclear utilities move towards interim storage for their reactors. Defense wastes, originally a one-tenth share of the Yucca Mountain project, are an additional option to decrease costs for the regional borehole case. Many defense-related wasteforms can be disposed of in deep boreholes, including but not limited to cesium and strontium capsules. These wasteforms could be accepted by a regional facility on a contractual basis, as could any out-of-region SNF (presumably at a higher cost). These scenarios require further analysis. The canister loading and design process should be covered more completely in a future work, although the estimate for canister loading cost range is close to SNL's estimate. Across the board, the general assumption of higher-than-average unit costs for the region facility was verified.

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ACKNOWLEDGEMENTS

This work was made possible through a research aide appointment during Summer 2015 at Argonne National Laboratory. Christopher Wentland provided indispensable technical and debugging support in quickly wrangling CALVIN to accept alternative inventories, cask designs, and scenarios.