Preliminary Design Concepts for a Deep Borehole Disposal Re-Packaging Facility – 14563

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ABSTRACT

As an alternative to conventional mined geologic repository strategies for the disposal of used nuclear fuel and high level radioactive waste, deep borehole disposal is potentially an inherently safe and cost-competitive method for the national task. With an estimated capacity of 200 MTHM of waste per borehole, an anticipated campaign of 700 boreholes could store the anticipated total of 140,000 MTHM of used nuclear fuel that would be generated by the current U.S. commercial nuclear fleet. Strategies for loading of individual waste packages range from 1 PWR or 3 BWR fuel assemblies to 2 PWR or 4 BWR fuel assemblies. Notionally, the waste packages would be canisters constructed of carbon steel, sealed by welds, and designed to maintain structural integrity primarily for the 40-day period required to load a single borehole. This paper evaluates different facility concepts for re-packaging commercial used nuclear fuel from large transportation casks and/or dual-purpose canisters (designed for storage and transportation) into appropriately-sized canisters for disposal in a deep borehole concept.

INTRODUCTION

The United States (U.S.) has focused its past efforts on disposing of used nuclear fuel (UNF) and high-level waste (HLW) in a mined geologic repository. The Blue Ribbon Commission for America's Nuclear Future (BRC) recommended prompt efforts to develop one or more consolidated storage facilities for UNF and one or more geologic disposal facilities for UNF and HLW [1]. Disposal in deep boreholes is one particular option that could potentially handle the national stockpile of UNF. The BRC also recommended "further RD&D to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach, particularly as a disposal alternative for certain forms of waste that have essentially no potential for re-use" [1].

The U.S. Department of Energy's Used Fuel Disposition Research and Development Campaign is investigating the deep borehole concept and has developed a research and development roadmap that describes the activities that could be conducted to help resolve key uncertainties about the deep borehole disposal concept and allow for a comprehensive evaluation of the potential for licensing and deploying such a facility [2].

Deep borehole disposal concepts have been developed [3] and conceptually utilize 5 kilometer-depth holes where waste packages are emplaced in the lower 2 kilometers of the hole. The waste packages are less than half a meter in diameter with a capacity of between one and four commercial UNF assemblies, depending on the fuel type. It is estimated that 700 boreholes, each storing 200 MTHM of UNF, would be needed to dispose of the projected 140,000 MTHM campaign of UNF to be produced by the nation's current commercial nuclear reactor fleet.

The U.S. reactor fleet discharges approximately 2000 MTHM of UNF each year. Because a disposition pathway is not available, the nuclear utilities have and continue to transfer UNF from the used fuel pools into large canisters or casks for storage at the reactor sites. The amount of UNF that would ultimately be transferred to dry storage depends on when acceptance of the UNF from the reactor sites begins and the rate that the UNF would be transferred from the reactor sites. It is estimated that between 5,000 to over 10,000 large canisters, with capacities exceeding 30 pressurized water reactor (PWR) or 60 boiling water reactor (BWR) UNF assemblies, could be used to manage UNF generated by the nuclear fleet [4].

Because the capacity of deep borehole disposal canisters is much smaller than the canisters currently used for UNF storage, a high throughput re-packaging facility would be required to deploy deep borehole disposal. UNF re-packaging facility concepts have been developed and evaluated for mined geologic repository concepts, however a re-packaging facility for a deep borehole disposal concept would likely be considerably different. This is because a larger number of disposal canisters would have to be loaded, sealed, and processed and also because of the potential for having to dis-assemble the UNF assemblies and consolidate the fuel rods to efficiently load deep borehole disposal canisters.

This study focused on the development of a design concept for a re-packaging facility co-located at the deep borehole site and devoted to accepting UNF from the commercial reactor fleet and re-packaging the UNF into a disposal canister for ultimate emplacement into a deep borehole. A preliminary investigation of the logistics and facility requirements needed to support disposal in a deep borehole was conducted.

Two approaches for UNF re-packaging were evaluated for their potential benefits with respect to cost, speed, and flexibility: 1) the re-packaging of intact UNF assemblies into deep borehole disposal canisters, and 2) rod consolidation yielding approximately 0.5 MTHM of waste per disposal canister. An economic analysis of these re-packaging options was performed, considering a range of factors associated with different re-packaging strategies.

DEEP BOREHOLE DISPOSAL RE-PACKAGING FACILITY CONCEPT

The operation of a UNF re-packaging facility at geologic repository consists of several UNF processing steps, including receiving, canister/cask opening, UNF assembly transfer, disposal canister closure, and disposal canister release. Several of these process steps would essentially be identical, regardless of the disposal concept (mined geologic repository vs. deep borehole). In particular, those process steps at the front-end of a UNF re-packaging facility and the associated processing bays, stations, or lines would not differ because the same types of UNF canisters/casks would be arriving and prepared for UNF transfer. Thus, the designs of transportation cask receipt bays, transportation cask preparation bays, and transportation cask unloading bays are not expected to be affected by the disposal concept.

Fuel transfer and disposal canister loading is expected to be quite different for a deep borehole disposal concept as compared to mined geologic disposal. The capacity of each deep borehole disposal canister, 1 PWR UNF assembly or 3 BWR UNF assemblies, is much smaller than canisters under consideration for mined geologic repository concepts, resulting in the need for a higher disposal canister production rate. Higher processing rates would affect the design of the fuel transfer system and the disposal canister closure system. As an example, vacuum drying of the loaded disposal canister may not be necessary because a deep borehole disposal concept is not likely to rely on the canister itself as an engineered barrier for post-closure repository performance. Furthermore, dis-assembling the UNF fuel assemblies and consolidating the fuel rods to increase the amount of UNF loaded into a single disposal canister may be beneficial with respect to total life cycle cost of the entire deep borehole concept.

A generic modular UNF re-packaging facility has been developed for creating disposal canisters for mined geologic repository concepts [4]. An isometric view of a 1,500 MTHM/yr re-packaging module is shown in Figure 1. This concept, the associated unit processing times, and associated unit costs [4] served as the basis for evaluating the re-packaging of intact UNF assemblies for a deep borehole concept. The dis-assembly of UNF assemblies and consolidation of UNF rods for loading into deep borehole disposal canisters was also considered and the design concept shown in Figure 1 was modified. It was assumed that 2 PWR UNF assemblies or 4 BWR UNF assemblies could be consolidated into a deep borehole disposal canister.

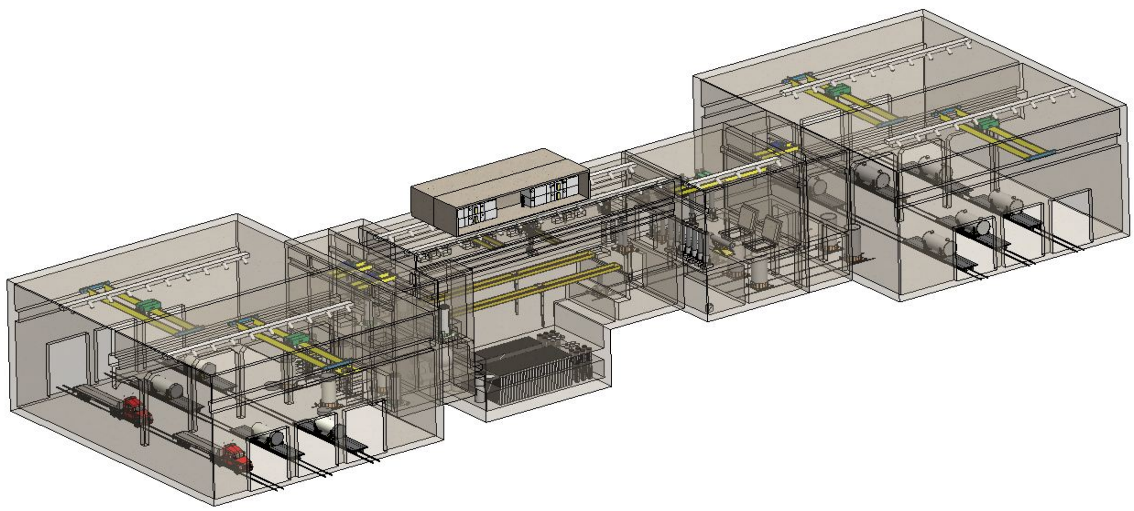

Fig. 1. Isometric view of the Overall Re-Packaging Facility Module Concept, including Carrier Receipt Bay, Airlocks, Waste Handling Building and Carrier Release Bay [4]

The idea of consolidating UNF rods into compact geometries originated in the 1960s, when nuclear utilities were exploring the options for expanding their pool storage capacity. Ultimately, the practice of spent fuel pool re-racking assemblies and at-reactor dry storage was chosen over fuel rod consolidation. As such, there has little development of this technology since the early 1990s.

Both wet and dry rod consolidation options were both explored and developed on a small demonstration scale in the 1980s and 1990s [5-7]. While slower, the wet rod consolidation of thousands of fuel assemblies per year in a pool provides an increased margin of safety in the event of off-normal events, such as processing delay due to operation failure in a UNF transfer station. In such events the fuel can remain in the pool without risk of degradation, overheating, and exposure to personnel. The Electric Power Research Institute completed a small-scale demonstration of a wet rod consolidation system and unit processing times based on those demonstrations is approximately 480 minutes for a single PWR assembly, and approximately 200 minutes for a single BWR assembly [6]. An automated wet fuel consolidation system designed by the Nuclear Assurance Corporation (NAC) in 1990 was chosen as the technology basis for rod consolidation considered in this study [8].

The most complete cost analysis available for fuel rod consolidation technology is found in a report on a prototypical demonstration of rod consolidation technology designed by NUS Corporation [9]. The consolidation technology was designed to operate in a dry hot cell environment, but has equipment that is very similar to those designed by NAC for wet pool operation. The estimated cost of the fuel rod consolidation equipment in 1989 U.S. dollars was $13M. Adjusted for inflation, the current equipment cost would be approximately $25M, incorporating an estimated $1M to modify the equipment for wet operation.

DEEP BOREHOLE DISPOSAL RE-PACKAGING REQUIREMENTS, CONFIGURATION, AND ROUGH ORDER OF MAGNITUDE COST

Three UNF disposition campaigns with UNF throughputs of 2000, 3000, and 4500 MTHM/year were considered. The current commercial nuclear fleet in the U.S. produces 2000 MTHM/year of SNF and the lowest disposition campaign matches the output rate of the commercial fleet. The other two disposition campaigns were chosen to evaluate the impacts of accelerated acceptance.

A total of 140,000 MTHM of UNF was assumed to be processed through the re-packaging facility. The TSL-CALVIN code [10] was used to conduct the logistic analysis of these campaigns and to determine facility configurations based on unit processing times. The rough order of magnitude life cycle cost (both capital and operating) of the facility was estimated using the same methodology used to estimate the life cycle cost of the generic modular UNF re-packaging facility shown in Figure 1 [4].

The configuration requirements of a re-packaging facility required for loading deep borehole disposal canisters with intact UNF assemblies and consolidated UNF rods are shown in Table I. It was assumed that vacuum drying of the disposal canisters was not required. However a sensitivity analysis was conducted considering both UNF rod consolidation and vacuum drying.

The simulation results show that the number of canister receipt lines needed is identical between consolidated rod and intact assembly disposal canister loading strategies, and that the number of lines scales with the throughput rate. The results also show that more UNF transfer stations are needed for rod consolidation because of the additional time required to first consolidate the UNF rods and load the disposal canisters as compared to loading intact UNF assemblies. The number of consolidation stations needed scales with the throughput rate.

A higher disposal canister processing rate is required when intact UNF assemblies are loaded into deep borehole disposal canisters because of the increased number of disposal canisters needed. In this scenario, disposal canister closing (welding) has the longest unit processing time and the number of closure stations needed varies with the throughput rate. More closure

TABLE I. Re-packaging facility configuration results

Loading Approach	Throughput Rate (MTHM/Year)	Number of operating lines for each process step				
		Canister Receipt	Canister Opening	Fuel Transfer	Disposal Canister Closure	Disposal Canister Release
Consolidated UNF Rods	2000	1	1	9	5	2
	3000	2	2	15	8	2
	4500	2	3	20	11	3
Intact UNF Assemblies	2000	1	1	2	7	3
	3000	2	2	2	10	4
	4500	2	3	3	13	5
Consolidated UNF Rods with Drying	2000	1	1	9	7	2
	3000	2	2	15	10	2
	4500	2	3	20	14	3

stations are needed for loading intact UNF assemblies into disposal canisters as compared to loading consolidated UNF rods. Including vacuum drying increases the number of disposal canister closure stations needed when loading consolidated UNF rods into disposal canisters.

The rough order of magnitude (ROM) total life cycle cost estimates are shown in Table II. Regardless of the disposal canister loading approach, the estimated ROM capital cost increases for higher throughput rates because of the need to deploy more processing lines and stations to handle the higher throughput. The estimated re-packaging facility ROM cost for intact assembly loading facility is less than that for a facility that loads consolidated UNF rods because of the reduced number of fuel transfer stations needed and the lower cost of each station. The capital cost increases as the throughput increases by a larger degree for a facility that consolidates UNF rods because of the increased costs of the fuel transfer stations. The need to vacuum dry the disposal canisters before closure further increases costs.

The estimated ROM operating costs do not necessarily increase with increasing facility throughput. The ROM operating cost is balanced between the labor force needed to run the facility and the operating period required to process the projected 140,000 MTHM of UNF through the facility. For example, a facility processing at a lower throughput rate will be smaller and need a smaller labor force, but would be operated longer in order to load all of the disposal canisters.

The estimated ROM operating costs for a re-packaging facility that loads intact UNF assemblies into disposal canisters is similar to or higher than for a facility that loads consolidated UNF rods.

Although the total number of processing stations and the labor force needed to run those stations is smaller, it is necessary to load approximately twice as many canisters. The additional cost of the canisters compensates for the reduced labor force needed.

TABLE II. Estimated rough order of magnitude cost of deep borehole disposal re-packaging

Loading Approach	Throughput Rate (MTHM/Year)	Capital ($B)	Operating ($B)	Total ($B)
Consolidated UNF Rods	2000	1.9	5.2	7.1
	3000	2.6	4.1	6.8
	4500	3.5	5.1	8.6
Intact UNF Assemblies	2000	0.9	5.2	6.1
	3000	1.4	5.3	6.6
	4500	1.6	5.0	6.6
Consolidated UNF Rods with Drying	2000	2.1	5.2	7.3
	3000	2.9	5.6	8.5
	4500	3.9	5.1	9.0

ROUGH ORDER OF MAGNITUDE COST ESTIMATES FOR DEEP BOREHOLE DISPOSAL INCLUDING RE-PACKAGING

A thorough assessment of the timing and costs involved for deep borehole disposal facility construction and operation has been completed [3]. The estimated costs are shown in Table III.

Table IV provides overall ROM cost estimates for the deep borehole disposal of 140,000 MTHM of UNF based on the values shown in Tables II and III. The estimated overall ROM cost is lower when a re-packaging facility is used to consolidate UNF into deep borehole disposal canisters compared to loading intact fuel assemblies into the disposal canisters.

TABLE III. Estimated costs of a single deep borehole disposal well [3]

Deep Borehole Construction Process	Estimate Cost ($M)
Borehole drilling and casing	27.3[a]
Waste package emplacement	2.8
Borehole sealing	2.5

Total	32.6

[a]Borehole Design 3 [Ref. 3, Table 5]

Table IV. Rough order-of-magnitude deep borehole disposal cost

Total re-packaging facility costs and deep borehole repository costs with full campaign of constructed boreholes assuming maximum borehole loading efficiency

Loading Approach	Throughput Rate (MTHM/Year)	Capital ($B)	Operating ($B)	Total ($B)	Borehole Repository ($B)	Combined Cost ($B)
Consolidated UNF Rods	2000	1.9	5.2	7.1	17.5	24.6
	3000	2.6	4.1	6.8	17.5	24.3
	4500	3.5	5.1	8.6	17.5	26.1
Intact UNF Assemblies	2000	0.9	5.2	6.1	35	41.1
	3000	1.4	5.3	6.6	35	41.6
	4500	1.6	5	6.6	35.9	41.6

The increased capacity of deep borehole canisters loaded with consolidated UNF (2:1 over intact UNF assemblies) requires half as many boreholes to accommodate the total UNF disposition campaign. Note that the capacity of each borehole is defined by the number of disposal canisters that can be emplaced into the borehole. A disposal canister loaded with consolidated UNF rods could hold approximately 0.9 MTHM of UNF, whereas a disposal canister loaded with intact UNF assemblies holds approximately 0.45 MTHM of UNF. Thus, higher capacity disposal canisters result in higher capacity boreholes when measured in terms of amount of UNF emplaced.

Given the importance of the cost of rod consolidation and the fact that this technology has not been developed for a long period of time, it is possible that the costs required to bring this technology to full production scales would be much greater than assumed in this evaluation. A sensitivity analysis was conduced to investigate the effects of increased rod consolidation costs where it was assumed that the costs were doubled ($50M per station).

While the estimated ROM operating costs were assumed to remain the same, the estimated ROM capital cost to construct the re-packaging facilities increases by approximately $1B. While the total cost of the facility is greater, it is not prohibitively more expensive to build and operate as compared to the overall cost that would be incurred by loading intact UNF assemblies into deep borehole disposal canisters.

CONCLUSIONS

A modular design concept has been developed for a facility to re-package commercial UNF into canisters for emplacement in a deep borehole disposal facility. The loading of both intact UNF assemblies and consolidated UNF rods into deep borehole disposal canisters was considered. Facility configurations were developed to meet required throughput for different UNF disposal campaigns. These facility configurations were then used to develop ROM total life cycle cost estimates for use in estimating the total ROM cost of deep borehole disposal.

The following conclusions and recommendations were drawn from this effort:

- Overall, the ROM total life cycle cost estimate for deep borehole disposal of commercial UNF is similar in magnitude to the costs of disposing the UNF in mined geologic repository concepts [4].
- The configuration of the re-packaging facilities for deep borehole disposal and resulting ROM total life cycle costs were found to be slightly lower than those previously estimated for re-packaging facilities for mined geologic disposal repositories [4]. Additional work is needed to understand the differences.
- Disposing of consolidated UNF assemblies in deep boreholes would increase the amount of UNF loaded into a single disposal canister, reduce the number of boreholes needed, and decrease the overall cost of deep borehole disposal. However, engineering development is required to further advance fuel rod consolidation technology to full production scales and to develop improved cost bases. However, deploying a re-packaging facility utilizing rod consolidation may still be economical even if the actual costs of the technology increase significantly.

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