A MULTIBRANCH BOREHOLE APPROACH TO HLW DISPOSAL

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A study was carried out to quantify the benefits of adapting the latest state-of-the-art in oil/gas well drilling technology to deep boreholes for disposal of spent LWR fuel or its post-reprocessing waste forms. It is now common practice to drill as many as a dozen side-wells at angles up to horizontal from a single vertical shaft. For HLW disposal this has several attractive features: significant cost savings; avoidance of excessive hydrostatic, canister stack crushing, and lithostatic pressures; and the need to securely plug many fewer vertical shafts.

A major subtask involved development of a computer code for predicting hole preparation cost as a function of more than a dozen key variables while allowing for parameter uncertainty. Enhanced geothermal system (EGS) cost data were employed to calibrate the code. The projected total cost of a US borehole repository field (including drilling, consolidating and encapsulating the fuel, emplacement and closure) was found to be about 70 $/kg HM for an optimized field of holes using ten 2 km long laterals inclined 20° from the horizontal.

Mechanical and thermal analyses were also carried out to confirm acceptable system performance over an indefinitely long post-emplacement history.

The overall conclusion is that this variation on the deep borehole HLW disposal option is well worth considering as a preferred alternative.

I. INTRODUCTION

The unsettled status of the US nuclear waste disposal program has led to renewed interest in the use of deep boreholes, drilled several kilometers deep into granitic basement rock, as an alternative. Most studies have considered vertical holes having a 2 km emplacement zone under 1 km of caprock, e.g., see Jensen this Conference[1] and Hoag.[2] The new work reported on here evaluates the application of state-of-the-art oil/gas multibranch well technology to nuclear HLW disposal because it offers both lower cost and enhanced confinement.[3]

Reference 4 describes multibranch drilling techniques, which have become progressively more sophisticated over the past two decades. Suffice it to note that commercial vendors can now provide holes of the type needed, in completed form with as many as a dozen lined side branches. Figure 1 shows in schematic fashion some of the many ways in which waste emplacement boreholes can be arranged around a single vertical mother hole. Table I lists typical parameters, and Table II summarizes pros and cons, focusing on differences which distinguish multibranch and single shaft boreholes.

The sections which follow address key issues carried over from the long history of similar evaluations done for shallower mined repositories, such as thermal loading limits and, of course, costs.

II. ANALYSIS OF THERMAL PERFORMANCE

One legacy of shallower mined repository assessments is a preoccupation with thermal conditions in both the waste canisters and the host rock. Borehole repositories, because of their inherently much smaller canister diameters (e.g., capable of housing only one PWR assembly) have a lower linear heat generation rate (W/m, see Table I) and would be expected to engender much less concern in this regard. However, quantitative confirmation is clearly called for. In the work reported here this was addressed using both analytic modeling in 1-D, and 2- and 3-D computer code (Solidworks) models of the bilateral configuration on the right in Fig. 1. Both approaches are rather straightforward, with performance dominated by conduction inside the simulated waste canisters and in the surrounding host rock, with radiation to and from steel canister walls and borehole liner steel tubes.

Table III summarizes the more important parameters involved.

Fig. 2 shows the time dependent temperature of the borehole wall calculated using the 2- and 3-D finite element code. As can be seen, it reaches a maximum of 145°C at about ten years after emplacement. The waste (consolidated PWR assembly) centerline temperature maximum occurs at the same time and is 181°C (not shown). Both values are quite tolerable based on Yucca Mountain requirements. Reprocessed waste forms, partly by design, have lower linear heat generation rates than reconstituted spent commercial fuel packages and should yield lower wall peak temperatures.

The 2-D model used a surrounding far-field host rock temperature of 100°C and adiabatic boundary conditions on all unheated surfaces with a unit cell representing a 200m by 60m block surrounding the emplacement hole (reflecting the vertical and horizontal spacing of repository laterals). The 3-D models five emplacement laterals in a granitic slab 3500m deep by 2500m wide and 100m thick. This model features fixed temperature conditions of 25°C at the surface and 109°C at 3500m with adiabatic boundary conditions on the remaining unheated surfaces. In both analyses, the finite element mesh was sized according to geometrical curvature of the model resulting in finest resolution near the heated borehole wall.

In Fig. 2 note that the 2-D results increase monotonically after several hundred years. This is because an unrealistic adiabatic rock cell wall boundary condition is imposed. The 3-D results correctly allow for vertical heat losses, and therefore decline monotonically after the initial peak. Hence this effect must be taken into account in borehole performance assessments.
The apparent discontinuities in the 3-D plot arise from tracking the temperature histories of finite element nodes at different points along the length of the borehole wall for the near, mid, and far term.

TABLE I. Multibranch Well Characteristics

Host Rock		
	Type: basement granite with < 500 m sedimentary overburden	
	Key properties:	
	< 10 microdarcy permeability	Improves with depth
	< 1% porosity	Improves with depth
	benign pH: >6, <9	
	reducing chemistry, E_h < 0.1 volt	
Boreholes		
	Plug zone length = 1500 m	
	Spacing between vertical kickoffs: > 30 m	
	Radius of curvature ≥ 230 m	
	Emplacement branch lengths ~ 2000 m	
	Branch vertical slope ≤ 1:5	
	Number of branches: 10 (ref. design)	
	Lateral bit dia: 11.625″ (29.5 cm)	
	Liner pipes: 26″ (17.5″/11 5/8″)	
	Total capacity: ~ 4000 canisters;	
	Sufficient for one 1 GWe PWR over its 60-80 year lifetime	
Waste Package		
	19.5 cm OD, 5 m long	
	P-110 drill string steel	
	301 PWR fuel pins (close packed)	
	(compare to 264 fueled rods in typical 17 × 17 assembly)	
	Post-reactor cooling: 40 years	
	Initial linear power at time of emplacement: 37 W/m	

TABLE II. Multibranch Well Attributes

A. Advantages of Multibranch Boreholes
As many as a dozen side branches can be drilled per central vertical hole, hence:
- Easier to have greater average depth of waste entombment zone
- The absence of a self-heated vertical chimney effect on water buoyancy eliminates a hypothetical escape mechanism
- Considerably lower cost due to reduced drilling time and rig relocation
- Only one plug needed in caprock zone; it can be longer and more elaborate
- Eliminates crushing of lower canisters by the stack above

B. Disadvantages of Multibranch Boreholes
Commercial experience is with smaller diameter side branches than for vertical-only wells, hence:
- This favors reconstitution of PWR (but not BWR) spent fuel bundles – at added expense
- Thus reprocessed waste forms are preferred
- Retrieval is more difficult, especially after plugging

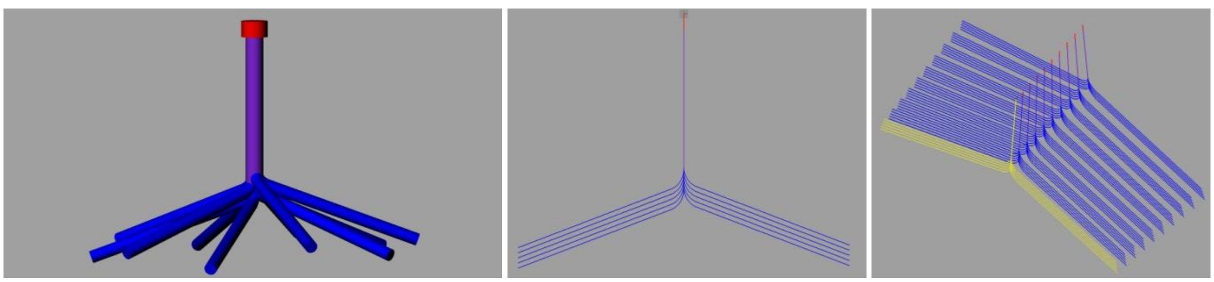

Fig. 1. Schematic of potential multibranch borehole configurations (hole diameters at left greatly exaggerated).

TABLE III. Summary of Thermal Design Study Properties and Parameters

Granite Material Properties	
Thermal conductivity	2.2 W/m-K
Density	2500 kg/m^3
Specific heat capacity	790 J/kg-K
Repository Properties	
Surface temperature	25°C
Subterranean thermal gradient	24°C/km
Cooling time before emplacement	40 years
BWR fueled length	4.1 m
PWR fueled length	4.2 m
Shaft spacing	200 m
Borehole spacing	5 km
Canister, Waste and Fill Thermal Properties	
Steel thermal conductivity	50.2 W/m-K
Steel (oxidized) emissivity	0.79
PWR & BWR fuel pin thermal conductivity	1.87 W/m-K
Void space fill thermal conductivity	0.33 W/m-K
Borehole wall diameter	29.5 cm
Waste canister ID	18.1 cm
Initial linear power	37 W/m

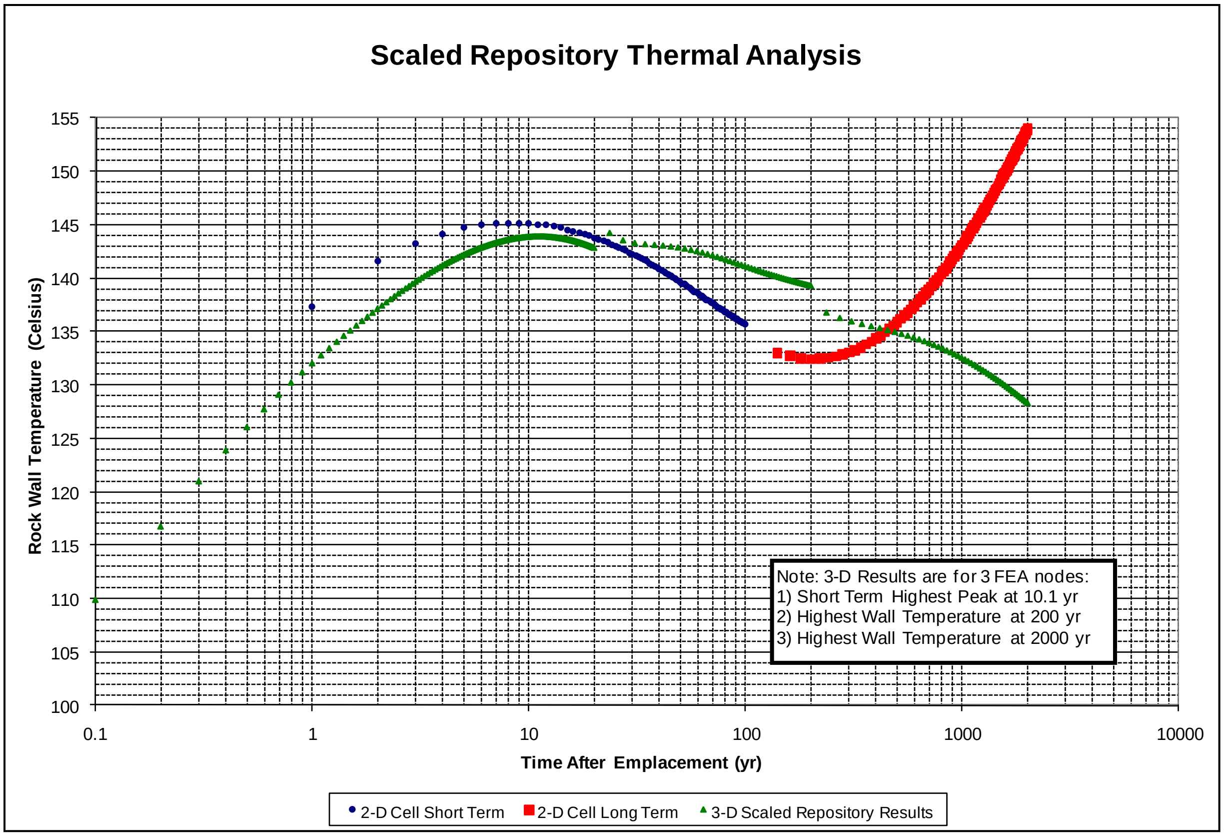

Fig. 2. 2-D and 3-D repository thermal results (PWR waste package).

III. COST MODELING

Since oil and gas well drilling cost parameters are, for the most part, commercially proprietary information, a major effort was mounted to develop a comprehensive, detailed computer program which could serve to cost out and hence optimize multibranch borehole designs (as well as single shaft vertical versions).

The model encompasses borehole drilling, completion, waste emplacement, and hole sealing. Figure 3 shows the generic geometry considered, in which length, depth, angle from the vertical, diameter and number of laterals are all specifiable descriptors. Sampling from probability distributions is employed for drilling speed and bit life (hence time consuming replacement trips); otherwise all parameters are deterministic in nature. The code can take into account seven geometric variables, five speed parameters, five task times, seven cost parameters and eleven spent fuel parameters. An array of sixteen drill/drill string parameters, each described by nine properties, is built into the code's internal database. A total of thirteen computed output values are generated, the most important of which are drilling time and cost.

Code parameters were vetted by oil industry experts, and the code itself was verified against a published single shaft enhanced geothermal system, EGS, borehole design and cost prediction. It was then employed in a long series of parametric studies on major variables, of which hole diameter and length proved most sensitive. Costs were found to vary essentially linearly with parameter magnitude.

Hence it was possible to develop linear regressions for the major parameters and their uncertainties (i.e. σ values).

Drilling time was by far the most important single determinant of the unit cost of waste disposal, \$/kg, and billing rate the most important input parameter.

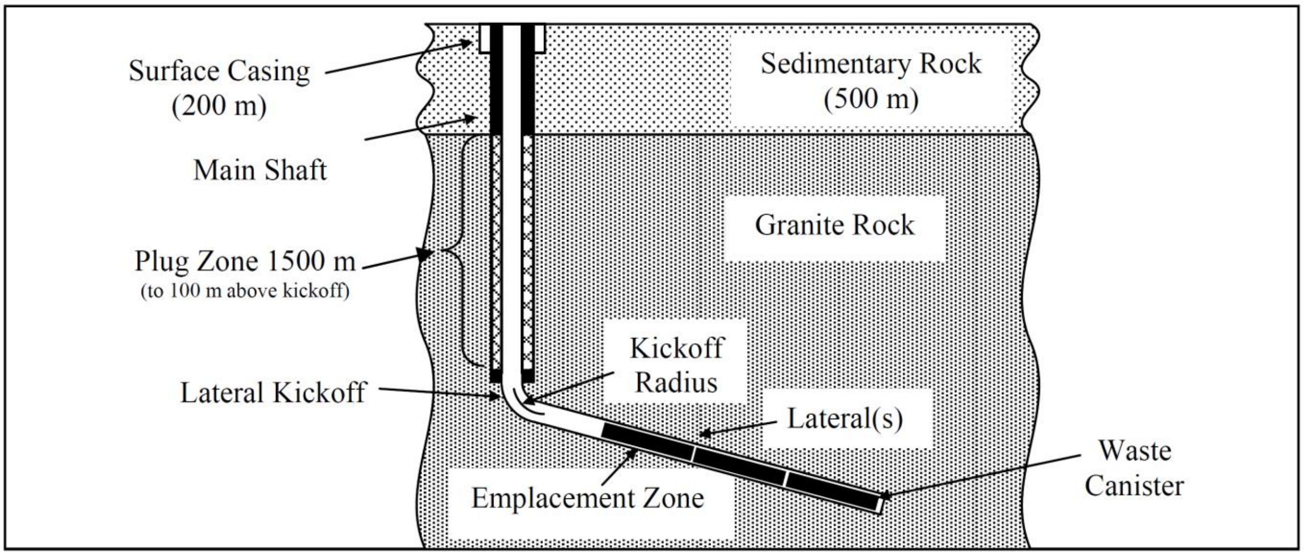

Fig. 3. Nominal repository configuration – only one of many laterals shown.

The best overall case selected from some 20,000 potential repository configurations had features as follows:

- A 1500 meter vertical plug section for adequate isolation of the nuclear waste from the biosphere
- 10 laterals extending from each vertical borehole
- 2000 meter long lateral emplacement shafts (400 packages/lateral)
- Laterals declined 20° from horizontal
- Drill-bit schedule calling for 26″ for the surface shaft, 17 ½″ for the main vertical shaft and 11 5/8″ for the laterals and radial kickoffs
- The vertical shaft is lined and cemented at depths below 2100 m, above which all casings are removed to permit direct contact of the borehole plug with the exposed granite rock face
- Laterals are also lined with casing but these liners are not cemented in place.

Part of the code's graphic output is shown in Fig. 4. Note the periodic interruptions as each lateral drift is completed and filled with waste canisters. Smaller ripples due to drillbit replacement are harder to see, but suggest that advanced drilling technology may be beneficial in this regard. Also note the linear accrual of expenditures with time. Again advanced technologies currently undergoing RD&D could reduce costs significantly: some proponents claim speedup by factors of 2 – 5.

One important conclusion is that, as a result of the highly detailed modeling of thermal effects and drilling costs, it will be possible in the future to employ far simpler formulations for borehole system design. Based on the modeling in this project, drilling and emplacement costs for this repository configuration are unlikely to exceed \$54/kg HM (median 51.2 \$/kg; μ 51.3\$/kg; σ 0.919 \$/kg). Based on some conservative assumptions built into the model (mature drilling techniques only, equipment rental rates similar to those for a much larger diameter and deeper enhanced geothermal well) this cost estimate should be considered an upper limit on directional drilling costs for lateral emplacement. Additional costs for waste package fabrication, SiC fill, fuel pin consolidation and canister sealing are expected to not exceed \$16/kg of HM for LWR spent fuel packages. These costs are significantly lower for reprocessed or vitrified wastes as they may be packaged into the final disposal canister at the source site. Taken together, all costs expected for a very-deep borehole approach amount to about \$70/kgHM, well within the DOE's waste fund fee (equivalent to ~\$400/kgHM) even when transportation costs to the repository and research and development costs are considered. The multi-branch lateral emplacement configuration is therefore demonstrated to be economically feasible. However, further tradeoff studies versus single-shaft vertical holes (e.g., Ref. 2) are still in order.

IV. CONCLUSIONS

Deep borehole disposal of high level wastes from nuclear reactor spent fuel has many attributes which recommend this approach as a serious alternative to the use of shallower mined repositories, and multibranch versions in turn have much to recommend them over single-shaft boreholes. Even better assurance of waste confinement is the principal attraction. The major impediment is not technological, but the policy decision of how much emphasis to put on long-term retrievability. Costs appear quite attractive, roughly $70/kgHM compared to the ~$400/kgHM provided by the current 1 mill/kWhre waste fee. The savings from multibranching override extra costs due to the need to reconstitute PWR fuel assemblies – a cost not incurred if reprocessed waste forms are involved. Finally, the upside of hole diameter limits is that thermal limits on both the waste and host rock are easily met, with large margins.

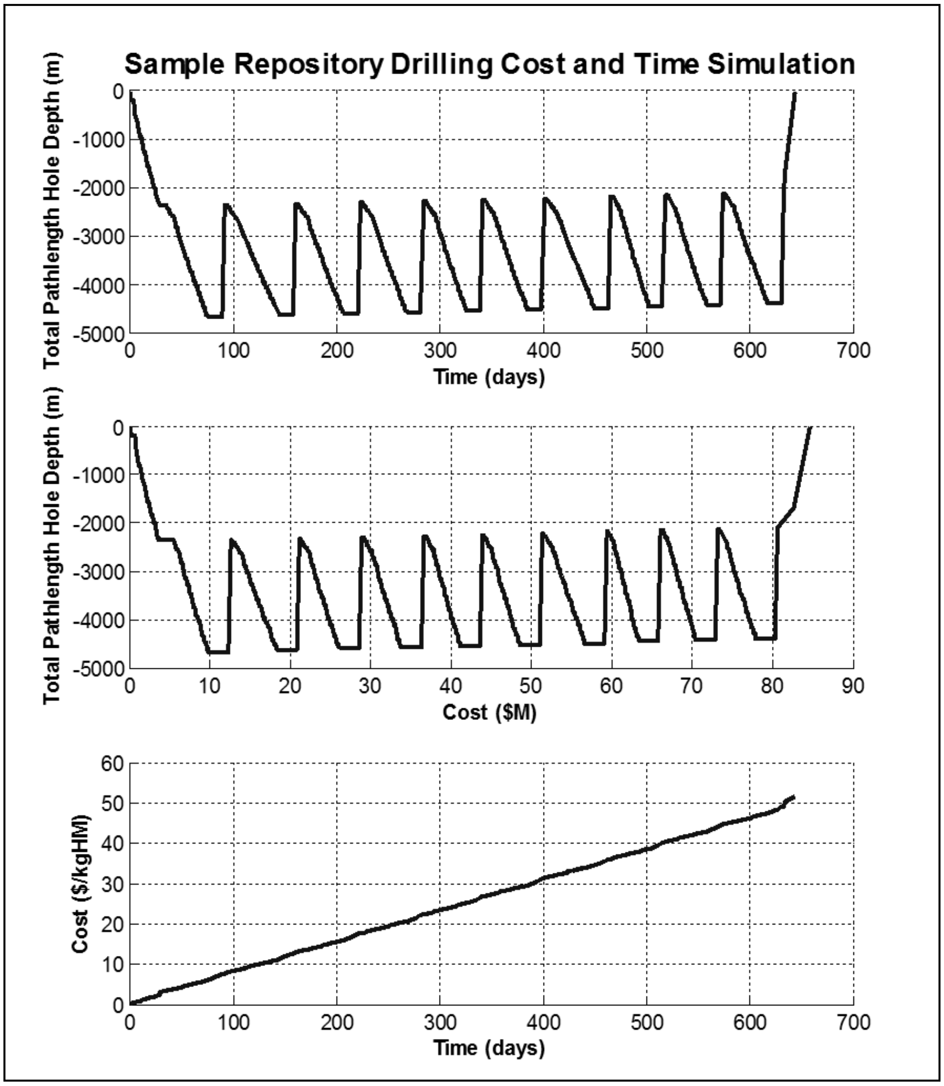

Fig. 4. Sample realization of final repository design.

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DROP-IN CONCEPT FOR DEEP BOREHOLE CANISTER EMPLACEMENT

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Disposal of high-level nuclear waste in deep boreholes drilled into crystalline bedrock (i.e., "granite") is an interesting repository alternative of long standing. Work at MIT over the past two decades, and more recently in collaboration with the Sandia National Laboratory, has examined a broad spectrum of design aspects associated with this approach. Past reports suggest using steel cables to lower each canister into the borehole. This process would require many years to complete and precise control to safely lower the canisters thousands of meters. The current study evaluated a simple, rapid, "passive" procedure for emplacement of canisters in a deep borehole: free-fall release into a water-flooded borehole. The project involves both analytic modeling and 1/5th scale experiments on a laboratory mockup. Experiments showed good agreement and validated the model. Depending on the inputs used for the mass and dimensions of the full scale canister and the viscosity of water, the model predicted terminal velocities of 2.4-2.6 m/s (4.5-5.8 mph). These estimates are conservative as they assumed a hydraulically smooth canister surface. Based on these predictions, there seems to be little risk of damage when a canister bottoms out on a stack of previously loaded canisters. For reference, dropping the canister in air from a height of only 0.3 m (1 ft) would result in an impact velocity of 2.44 m/s. It is concluded that a simple drop-in procedure deserves serious consideration for adoption as a standard procedure for borehole loading.

I. INTRODUCTION

The unresolved issues of long term nuclear waste disposal in the United States remain a limiting factor in the expansion of nuclear power- a proven and carbon free energy source. Work on the Yucca mountain repository has been suspended, and a Blue Ribbon Commission appointed to recommend a new path forward. Deep borehole waste disposal (DBWD) has been proposed as an attractive alternative to shallow mined repositories. The deep borehole disposal strategy involves drilling and lining a borehole a few kilometers (e.g. 4 km) down into a region of the Earth's crust which mainly consists of granite. Canisters containing spent nuclear fuel are stacked in the lower 2 km of the hole, while the upper region is sealed off with a multilayer plug (bentonite clay, asphalt, and cement for example). A schematic of the DBWD concept is shown in Figure 1.

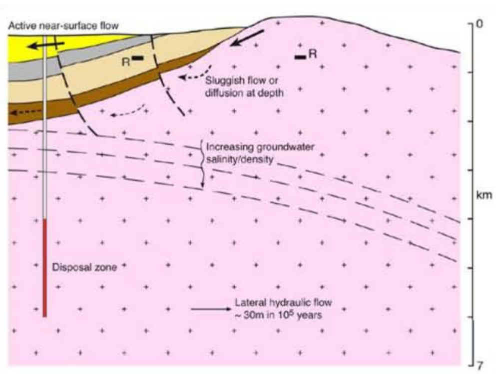

Fig. 1. Cross section of the deep borehole concept. Geologic conditions with reduced water flow are a main component of the added safety of deep boreholes.[1]

This disposal technique is promising for a number of reasons. Waste in boreholes is significantly deeper and further away from water sources compared to typical shallow mined repositories. This naturally results in better isolation of radionuclides from the surface and humans. Deep granite rock is typically a chemically reducing environment, which reduces radionuclide solubility and decreases their mobility.[1] In addition, the performance does not depend as heavily on engineered barriers, which have greater long term uncertainty associated with them. Preliminary performance assessments of DBWD have estimated the peak radioactive dose to a human to be many orders of magnitude less than the internationally recommended limits for post-closure dose.[1] Furthermore, since solid granite formations are relatively common at depths of 2-5 km in the United States, DBWD increases the number of potential sites for waste repositories. It currently is the only widely researched alternative to mined repositories and has had substantial attention from researchers at Sheffield University in the UK, SKB in Sweden and MIT in collaboration with Sandia National Laboratory.[2,3,4,5] The growing interest in enhanced geothermal systems, which utilize similar technologies and methods for drilling into granite, has greatly improved the feasibility of borehole disposal.[6]

The main areas for improvement to the deep borehole disposal concept are site selection criteria, borehole fill materials, emplacement facility details and performance risk assessments. The objective of this study was to provide experimental and analytical findings to support economic solutions for emplacement facility operation.

I.A. Emplacement Issues and Motivation

According to a recent study of drilling technology for DBWD, drilling a borehole to a depth of 4 km with a 0.5 m diameter is perfectly practicable.[7] This study estimated that the process of drilling a single borehole would require nine months, whereas the emplacement of waste packages and filling of a borehole could take 6 to 24 months. Another feasibility study, commissioned by SKB and completed by drilling industry consultants, estimated that the drilling task would take approximately 130 days and 4 million Euros (€ 2000) (Ref. 8). After drilling, the next task in the emplacement process is the safe stacking of canisters (400 canisters with 0.5 metric tons of heavy metal each). Considering that 400 of these boreholes are needed to contain 80,000 metric tons of waste (approximately equivalent to the capacity of the Yucca mountain repository), reducing the time for emplacement is a key factor in reducing the total cost of the repository.

For deployment, the SKB study suggested the following technique.[8] First the borehole is drained of the drilling foam (used during the drilling phase to facilitate the removal of drilled rock and debris). Then the borehole is completely filled with deployment mud. Using the original drilling rig, the canisters (with Kevlar or plastic longitudinal fins attached) are forced through deployment mud until they reach the 4 km deep deployment zone. Eight shearing pins, used to ensure that accidental release is impossible, break when the rig provides the appropriate set down weight of 18 metric tons thereby releasing the canisters. Special grease is inserted into the canister's fishing neck, to ensure that retrieval is possible using the same method. The study did not go into the details of time or cost for this process.

Another evaluation, consistent with oil and natural gas experience, suggested the use of steel cables to lower each canister into the borehole.[9] The time required for this technique may be an issue. For example, a high capacity deep ocean winch operates at approximately 2 m/s (Ref. 10). Optimistically assuming a winch speed of 2.9 m/s, a one-at-a-time approach requires 240 hours to lower all 400 canisters into a single borehole. This also assumes a 6 m/s retrieval speed for the unloaded string and 10 minutes to attach a canister onto the crane. Using estimated billing rates[9] the operational cost of loading a single borehole in this fashion is at least $1.6 million. This is the same order of magnitude as the drilling cost. Dividing the cost by the total waste contained in a borehole, the deployment stage cost per unit mass is approximately $8/kg of heavy metal. This estimate factors in a higher billing rate only during the attachment of a canister onto the crane, when radiation workers will be required to supervise the process. In total, a crane would take 955,000 hours (approximately 11 years) to stack all 1600 canisters for a single repository.

Alternatively, stringing five canisters together would save on deployment time, requiring only 130 hours and $1.2 million per hole. However, it would require substantially higher rated winches and cranes and an estimated hour of costly radiation worker labor per connection of five canisters.[9] Furthermore, the non-rigid, 25 meter tall string of waste canisters would be conceivably more difficult to lower accurately into the borehole lining pipe. The risk from human error, accidental drop, and additional radiation exposure would also have to be further analyzed.

Economics and safety are the two primary driving forces in the nuclear industry. As a result, it is desirable to reduce the cost, complexity and number of components needed for the emplacement system to operate reliably. Current estimates show the total costs of DBWD to be equal to or above the cost of the currently accepted disposal strategy (mined repositories). This study attempts to improve the expense, speed and safety of the DBWD program by investigating a much less complex rig for the deployment stage. This has the advantage of freeing up the original rig to drill the next borehole, expediting the entire emplacement process and drastically reducing the costs of the entire program.[7]

II. PROPOSED DEPLOYMENT METHOD

The suggested alternative is to fill the borehole with water and drop the canisters into the flooded hole. As a precaution, a test canister which reports its velocity and location should be dropped first to ensure that the borehole has been lined correctly and there are no unexpected angles or obstructions. However, based on drilling experience, the directional accuracy of the borehole lining is not expected to be an issue. For example, when the KTB borehole- drilled in Germany- reached a depth of 7.5 km, the borehole had only deviated from its original axis by 12 meters (Ref. 11).

The key benefit of this method is that the borehole filling process will in theory only be limited by how fast the canisters can be loaded onto a crane and dropped into the water. Assuming 10 minutes of loading time per canister, a single borehole can be filled in approximately 65 hours. Furthermore, this method may transition more smoothly from the drilling stage, which leaves the borehole filled water or other viscous fluids. [10] Overall, this method of transport requires significantly less mechanical equipment and operator attention, and has few modes of failure.

A main goal of this study was to demonstrate that the canister will reach a safe terminal velocity and that the impact will not damage the canister significantly. The design and addition of drag inducing components are also investigated as an additional barrier to canister integrity failure. Fig. 2 shows the relevant properties of the full scale drop-in emplacement strategy.

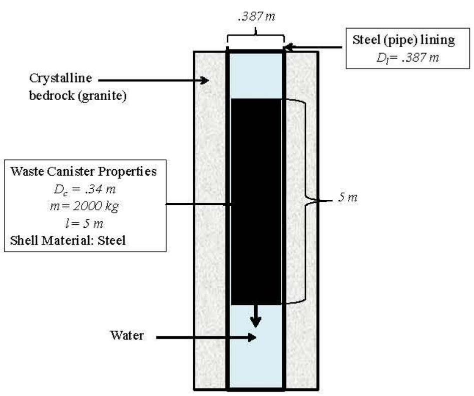

Fig. 2. Cross sectional view of the proposed emplacement method, based on Hoag's design for the pipe lining and canister dimensions[12]. Not to scale. Note that the gap between the canister is an annulus with a thickness of 2.35 cm.

III. THEORY AND PREDICTIONS FOR CANISTER TERMINAL VELOCITY

The analytic model is based on solving a force balance and momentum equations. A force balance diagram is depicted in Fig. 3.

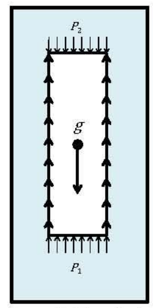

Fig. 3. Depiction of gravitational, shear and pressure based forces that act on the canister as it falls at terminal velocity.

The force balance on the canister can be written as,

$$P_1 - P_2 = \rho_C g l - \frac{\rho_f V_f^2}{2} f\left(\frac{l}{D_C}\right) \quad (1)$$

where P_1 is the liquid pressure acting on the top surface of the canister, P_2 is the liquid pressure acting on the bottom surface of the canister, ρ_c is the density of the canister, ρ_f is the density of the fluid, V_f is the average fluid velocity, g is the gravitational constant, f is the friction factor, l is the length of the canister and D_c is the diameter of the canister

The momentum equation for the fluid, taking into account form and frictional pressure drops, is written,

$$P_1 - P_2 = \frac{\rho_f V_f^2}{2}\left(f\frac{l}{D_h} + K_{form}\right) + \rho_f g l \quad (2)$$

where K_{form} is the form loss coefficient associated with the flow geometry, D_h is the hydraulic diameter (equivalent to twice the size of the annular gap).

III.A. Fixed water volume boundary condition

In this expected condition, the volume of the water beneath the canister was assumed to be constrained (and unable to flow in any direction besides through the annulus). In addition, the water was considered to be incompressible. Therefore, as the canister moves downwards, the water volume it displaces will be forced to flow through the annulus. The continuity relation yields,

$$\frac{V_f}{V_C} = \frac{{D_C}^2}{D_h(2D_C + D_h)} = V_{ratio} \qquad (3)$$

where V_f and V_c are the magnitudes of the canister and fluid velocities, respectively.

For Hoag's canister design, V_{ratio} is approximately 3.4 (the ratio of the average velocity of the fluid in the annulus to the velocity of the canister is 3.4). However, the fluid travels in the opposite direction of the canister. The relative velocity of the fluid to the canister surface is greater than the fluid's velocity in the stationary frame of reference. If the latter were assumed as the velocity of the water in the gap, it would significantly underestimate the frictional forces on the canister. To take this into account, the reference frame is shifted by a constant velocity, such that the velocity of the canister in the new reference frame is zero. This is acceptable because the momentum, continuity and energy equations apply in any frame of reference, as long as the frame is not accelerating. The calculation of the friction factor in the annulus will be slightly overestimated in this frame of reference, because the outer pipe has a small velocity that is in the same direction as the water flowing in it. No correlation could be found that describes the friction factor in an annulus with a moving boundary. By intuition, it is postulated that most of the shearing will occur near the surface of the canister, and thus it is more important to accurately model that phenomena/region. Furthermore, the experimental data will support this simplifying assumption.

Eliminating P_1 - P_2 from Eqs. (1), (2)and (3), the expression for terminal velocity for the canister in this case is,

$$V_C = \sqrt{\frac{2gl\left(\frac{\rho_c}{\rho_f} - 1\right)}{\left[f\left(\frac{l}{D_h} + \frac{l}{D_c}\right) + K_{form}\right](V_{ratio} + 1)^2}} \qquad (4)$$

Substituting the reference values from Hoag's canister design[12] and using surface water conditions yielded a modest canister velocity of 2.37 m/s. The friction factor f was calculated iteratively using the Colebrook correlation to be 1.30 x 10^{-2} (Ref. 13). K_{form} was taken from tables to be 1.5 (as the canister causes a sudden contraction and expansion of the flowing fluid)[14]. Assuming a granite and water temperature of 120 °C at the bottom of the borehole (hydrostatic pressure prevents boiling), the estimate for the terminal velocity rises slightly to 2.6 m/s. Overall, this approach is conservative because the friction factor was calculated assuming the canister and pipe are hydraulically smooth. Secondly, the canisters, which are designed to withstand very high compressive stresses from the upper (stacked) canisters weight, are expected to be able to absorb such a small impact without significant damage.

III.B. Open water boundary condition

Further analysis was completed to address a potential failure mode of the drop-in concept. This condition approximates a scenario where there bottom of the borehole is not sealed properly. In this case, the volume of the water beneath the canister is assumed to be free to flow downwards (or into another volume besides the borehole). Therefore, as the canister moves downwards, the water displaced by the canister will not be forced to flow through the annulus. This scenario is practically impossible for at least two reasons: (i) a massive rupture of the borehole lining is extremely unlikely, and (ii) there is no large free volume available for water displacement in granite. However, we analyze this scenario as a bounding case. Here, there is no simple relationship between V_c and V_w. In this situation, analysis of the boundary layer and velocity distributions are critical to understanding the shear forces on the canister. If the boundary layer is small compared to the actual gap, then the solution can be approximated by estimating the canister's velocity in a large pool of water. Under these conditions of external flow, the canister terminal velocity can be derived by using its coefficient of drag (approximately 1 for this case[15]) and force balance, which gives the expression,

$$V_c = \sqrt{2gl\left(\frac{\rho_c}{\rho_f} - 1\right)} \qquad (5)$$

Plugging in the reference values from Hoag's canister design, a physically feasible canister terminal velocity of 18.3 m/s was obtained, with a Re_{axial} of 6.6 x 10^6. The maximum size of the boundary layer was calculated as[13],

$$\delta = 0.16l(Re_{axial})^{-1/7} = 8.49\,cm \qquad (6)$$

In this case, the boundary layer is nearly 4 times larger than the actual gap that it is constrained to fit in. Therefore, the assumption of external flow is not valid, and can only be used to obtain an upper bound estimate of the canister velocity. In reality, viscous effects in the boundary are more important because the boundary layer is forced to fit in such a small gap.

The next approach estimated the velocity distribution in the gap using Von Karman's Universal Law.[14] Using the no-slip boundary condition, the velocity was constrained to be a maximum (and equal to V_c) at the surface of the canister, and zero at the outer lining diameter. With this approximate velocity distribution, a friction factor for flow in the annulus was derived to be,

$$\sqrt{\frac{1}{f}} = 0.8626\ln\left(\mathrm{Re}\sqrt{f}\right) - 0.588 \qquad (7)$$

Combining (7) with the approximated velocity distribution and force balance Eq. (1) and (2) yielded,

$$V_c = \left(1 + 0.8626\sqrt{f}\right)\sqrt{\frac{2gl\left(\frac{\rho_c}{\rho_f} - 1\right)}{\left(f\left(\frac{l}{D_h} + \frac{l}{D_c}\right) + K_{form}\right)}} \qquad (8)$$

Substituting the reference values from Hoag's canister design gave a canister velocity of 11.51 m/s. The terminal velocity in this extremely conservative bounding case can be put into perspective by considering the fact that the same velocity would be achieved if the canister was dropped in air from a height of only 6.75 meters (only 20% longer than the total length of the canister). In reality, the canister would have to be designed to withstand such an impact (in the case of an accidental drop when it is being lifted and emplaced).

IV. DIMENSIONAL ANALYSIS AND EXPERIMENT DESIGN

To test the validity of the analytical expression for terminal velocity - see Eq. (4) - a scaled down experiment was designed. Scaling was based on dimensional analysis to ensure that the experiment would simulate the conditions of the actual borehole as closely as possible. The relevant design variables were found from inspection of Eq. (4) and (8), and are presented in Table I.

TABLE I. Definition of All Relevant Variables and Their Respective Dimensions, where *M* Stands for Mass, *L* stands for Length, and *T* stands for Time.
**Note that the Hydraulic Diameter for a concentric annulus is equivalent to 2t.*

Abbreviation	Description of Variable	Dimensions
D_c	Diameter of Canister	L
t	Gap Thickness	L
D_h	Hydraulic Diameter*	L
l	Length of Canister	L
ρ_c	Density of Canister	$M/(L^3)$
ρ_f	Density of Fluid	$M/(L^3)$
μ	Viscosity of Fluid	$M/(LT)$
g	Gravitational Constant	L/T^2
ε	Surface Roughness	L
V_f	Velocity of Fluid	L/T

Since there are 9 variables and 3 dimensions, there are 6 dimensionless parameters that describe the system. They are the Reynolds number:

$$Re = \frac{\rho_f V_f D_h}{\mu} \qquad (9)$$

which represents the velocity of the canister and thus is the dependent variable. The geometric and material property ratios:

$$\frac{\varepsilon}{D_h}, \frac{L_c}{D_h}, \frac{D_c}{D_h}, \frac{\rho_c}{\rho_f} \qquad (10)$$

and the Archimedes number *(Ar)*, which captures the buoyancy effects.

$$Ar = \frac{\rho_f(\rho_c - \rho_f)g{D_h}^3}{\mu^2} \qquad (11)$$

Then the Buckingham Pi Theorem ensures that,

$$Re = f\left(Ar, \frac{\varepsilon}{D_h}, \frac{L_c}{D_h}, \frac{D_c}{D_h}, \frac{\rho_c}{\rho_f}\right) \qquad (12)$$

The test facility scaled down all geometric and material parameters approximately by a factor of 5, to fit in the lab space. The test section consisted of a 2 m long, water filled, 7.62 cm ID acrylic tube. The canister was a 0.98 m long, 6.7 cm OD plastic tube, and its density was adjusted using lead particles to achieve the correct density ratio. A comparison of dimensionless parameters is shown in Table II.

TABLE II. Dynamic similitude of experimental parameters

Dimensionless Groups	Full Scale	Experimental
Ar	3.46×10^9	1.7×10^7 – 2.5×10^8
$\frac{\varepsilon}{D_h}$	9.78×10^{-4}	1.63×10^{-4}
$\frac{L_c}{D_h}$	106.4	106.6
$\frac{D_c}{D_h}$	7.23	7.26
$\frac{\rho_c}{\rho_f}$	4.4	2.4 – 4.3
Re, predicted using (4)	4.24×10^5	2.4×10^4 – 1.1×10^5

Using the actual value for the roughness of steel, the relative roughness ratio is not exactly matched. However, for the purposes of predicting conservatively high velocities, the pipes in the full scale case were assumed to be hydraulically smooth. Surface roughness will be investigated in future experiments as a means of inducing drag.

Thus, the only unmatched independent group is Ar. This cannot easily be matched because it is difficult to find safe fluids with dynamic viscosities sufficiently lower than water to compensate for the 1/5 reduced geometry (D_h in Eq. (11)). Note that experimental results discussed in Section V show the correlation between the Ar and Re to be fitted by the curve:

$$Re = Ar^{0.49} \qquad (13)$$

which indicates that the effect of the Ar on Re becomes weaker at higher Ar. Thus, it was deemed safe to extrapolate into this region of interest and the scale experiments were concluded to simulate the relevant physical phenomena accurately.

Velocity was measured using a light-weight line attached to the top of simulated canisters and wound around a rotary motion meter's pulley. Software recorded the rotational velocity of the meter. The terminal velocity was calculated by determining the time interval over which velocity remained relatively constant and averaging the velocity values in said interval.

Temperature (and thus viscosity) was varied by insulating the pipe and beginning the experiment with >90° C water. Over the course of many hours as the temperature fell, the canister was repeatedly dropped as the temperature and velocities were recorded. The low friction pulley and a series of tests eliminated rotary drag from concern.

V. EXPERIMENTAL RESULTS

Figure 4 summarizes the results of over 50 drop tests which varied the Ar by adjusting fluid temperature and canister density. Ar was first varied (under constant, room temperature water conditions) by changing the density of the canister from 2300 kg/m^3 to 4260 kg/m^3. To obtain an even higher Ar (to match the full scale case as closely as possible), Ar was varied by adjusting the temperature of the water in the pipe between 48°C and 92°C. This allowed μ to be changed over the range of 0.315 to 1.002 $N\text{-}s/m^2$ x 10^3, while ρ_c was kept at 4150 kg/m^3.

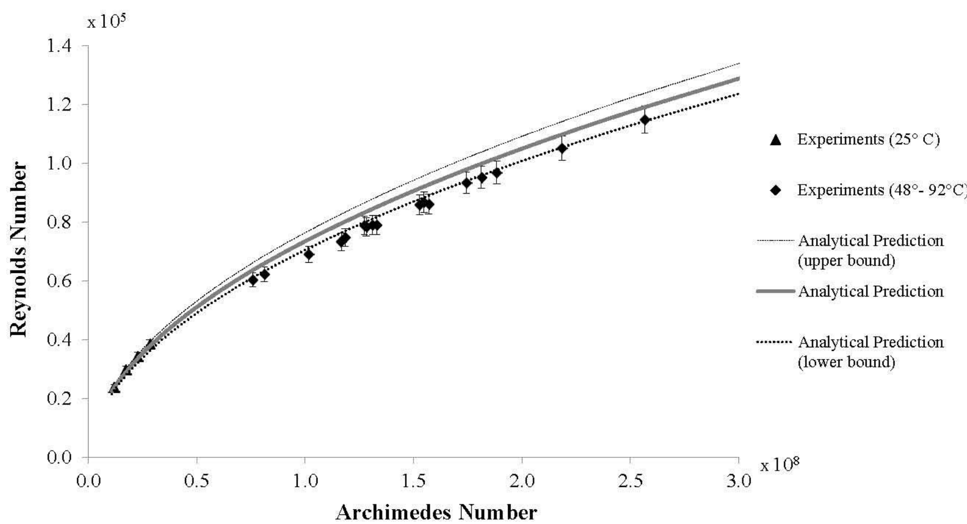

Fig. 4. Comparison of analytical model predictions to experimental data obtained through variation of μ, ρ_f and ρ_c.

As can be seen, agreement with the analytical model is very good, which gives us confidence to use it for prediction of the terminal velocity in the actual borehole. The uncertainty in model predictions, as shown by the upper and lower bound curves in Fig. 4, is very sensitive to the accuracy of the canister diameter measurement. Digital calipers measured within ± 0.1 mm and the canister diameter was not uniform over the entire length. At this scale, the velocity of the canister is strongly influenced by changes in the gap thickness, even to 0.1 mm, because the size of the gap is only 4.6 mm. Furthermore, thermal expansion of the canister and pipe at high temperatures also increased the uncertainty of the gap thickness.

Additional experiments were completed to determine the effect of a drag inducing feature (in this case a rubber disc axially stood off 5 cm in front of the canister). The disc was modeled as a form loss and treated as a sudden contraction and expansion (addition to $K_{form} \sim 1$). Using these assumptions, the model predicts that a single disc reduces the terminal velocity by approximately 10-15%. In four experiments run at water temperatures between 72°C and 77.5°C, the modified canister's terminal velocity was more than 10% lower than the unmodified canister velocity in previous experiments. Therefore, it was concluded that the analytical model can account for the effect of a drag inducing feature, although further experiments will investigate alternative geometries to confirm this.

VI. CONCLUSION

Use of deep boreholes to contain nuclear waste has been gaining more attention as pressures to deal with nuclear waste rise. The complexity and cost of the emplacement procedure is a challenge to the concept's feasibility. This study evaluated a fast procedure for emplacement of canisters which reduces mechanical and radiation handling requirements. The proposed method is to release the canisters into a water-flooded borehole with velocity moderated by drag forces developed in the fluid flow process. An analytical model, dimensional analysis, and 1/5th scale experiments were completed. The model was validated by the experimental results and predicted a maximum velocity of 2.4-2.6 m/s (4.5-5.8 mph) for the full scale case. Future work will test the effect of canister surface roughness on terminal velocity, and a structural analysis will be completed to determine the effect of the impact on canister integrity.

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