Webinar Q&A
May 2021

Safety in Depth Part 2: Sealing of a Deep Horizontal Borehole Repository for Nuclear Waste Q&A

Deep Isolation, Inc.
Berkeley, California
USA

May 24, 2021

This work was supported by Deep Isolation, Inc., Berkeley, California, USA.

This document serves to respond to public comments received by Deep Isolation on March 30/31, 2021, during a recorded webinar titled “Safety in Depth, Part 2: “Sealing of a Deep Horizontal Borehole Repository for Nuclear Waste.”

In this webinar, Deep Isolation shared results from a post-closure safety analysis of a repository in which the access holes and horizontal disposal sections are poorly sealed. A poorly sealed borehole could potentially provide a preferential path for contaminated groundwater to flow from the depth of the repository to a near-surface aquifer. The impact of poor borehole sealing on radiological exposure dose was examined. The study is documented in a peer-reviewed journal article. Note that the article does not address the design, optimization, and long-term effectiveness of the various borehole sealing materials; the purpose of the paper was to examine the consequences if such sealing methods were to fail.

The names of individuals asking questions have been excluded for privacy reasons. The answers provided by Deep Isolation address all questions received in relation to the webinar, including those on topics beyond the borehole sealing issue, which was the main topic of the webinar and the related journal article.

Some of the questions may have been edited for clarity and brevity.

Table of Contents

Borehole Sealing Questions

1. Is the borehole seal a barrier? If so, how could the barrier capability be described and supported technically?

Borehole seals, plugs, backfills, and buffers act as mechanical, hydraulic, and chemical barriers. However, Deep Isolation's analysis (documented in https://www.mdpi.com/1996-1073/14/1/91/pdf) shows that a potential leakage through a poorly sealed borehole would be very small and does not impact repository performance. Even though no credit needs to be taken for effective borehole sealing in a safety assessment, Deep Isolation plans to properly plug, seal, and backfill the access hole to the repository.

2. How does sealing a horizontal borehole differ from sealing a vertical borehole?

Identical methods can be used to seal the access structures of a vertical or a horizontal borehole repository, as the access hole is vertical in both concepts. Plugs and seals can be installed in vertical, slanted, or horizontal boreholes, potentially requiring some adjustments or different designs to account for the different role that gravity may play during installation.

3. Has Deep Isolation reviewed and considered the extensive history of "stemming" for the ~900 underground U.S. nuclear tests?

The stemming methods used for the sealing of boreholes completed for underground nuclear testing are similar to those investigated by nuclear waste disposal organizations, even though the conditions (and thus sealing requirements) are different between the two applications. Please note that Deep Isolation's work reported in https://www.mdpi.com/1996-1073/14/1/91/pdf does not address the design, optimization, and long-term effectiveness of the various borehole sealing materials and methods, which have been extensively investigated. The purpose of the paper is to examine the consequences if such sealing methods were to fail.

4. How will the native material and sealing materials interact to ensure long-term containment?

We expect to use native materials to plug, seal, and backfill the borehole. This approach reduces the development of interfaces with contrasts in chemical and mechanical properties. Over time, the native materials are expected to reform the bond and enhance long-term containment. For example, shale will creep to seal potential gaps between the backfill and the borehole wall as well as fractures in the drilling disturbed zone. Please note that Deep Isolation's work reported in https://www.mdpi.com/1996-1073/14/1/91/pdf does not address the design, optimization, and long-term effectiveness of the various borehole sealing materials and methods, which have been extensively investigated. The purpose of the paper is to examine the consequences if such sealing methods were to fail.

5. Have borehole-matrix interaction parameters been confirmed or tested with any experimental data?

The interface between the borehole sealing material and the surrounding geologic formation has been studied extensively through theoretical analyses, as well as experimentally in laboratory setups and field settings, specifically in dedicated underground research laboratories (URLs). This interface is indeed a critical element of the sealing system. However, please note that Deep Isolation's work reported in https://www.mdpi.com/1996-1073/14/1/91/pdf does not address the design, optimization, and long-term effectiveness of the various borehole sealing materials and methods. The purpose of the paper is to examine the consequences if such sealing methods were to fail.

6. Your results are highly sensitive to assumptions about the nature of the overburden, whose high permeability currently offers a high degree of dispersion[*]. If the overburden is as tight as the host rock, the release up the borehole would presumably be greater.

It is correct that the release of radionuclides through a poorly sealed borehole would increase if the formation above the repository were as tight as the host rock itself. However, this is unlikely to be a factor of high sensitivity. The absolute release rate through the borehole and, in particular the peak exposure dose rate, are still expected to be small for the following reasons:

(1) Even if the permeability of the overburden were as low as that of the host rock, there would still be radial diffusive releases across the relatively large cylindrical interface between the borehole and the formation. The effective diffusion coefficient might be smaller than in the case of a higher permeable overburden, but diffusive losses would still occur. This effect is similar to that of "matrix diffusion" in a fractured system, which greatly retards radionuclide transport.

(2) The cross-sectional area available for advective transport along the borehole is small. Such advective transport can only occur if a considerable overpressure is generated within the repository's disposal section, and if a sufficient water supply were available to sustain the pressure gradient and the advective upflow.

(3) If the overburden were as impermeable as the host rock itself, the repository would be very well isolated and releases through the geosphere would be very small. Since releases through the geosphere are likely to dominate radionuclide concentrations in an aquifer, the peak exposure dose would be reduced despite a potential increase of releases through a poorly sealed access hole.

(4) It is difficult to find a geological region with a very tight, "host-rock-grade" formation extending from the land surface to the depth of the repository (1-3 km). Our model is based on reasonable assumptions about the properties of a typical overburden (carbonate, marl, sandstone, shale, etc.).

To summarize, we believe that the results of the safety calculation assuming a poorly sealed hole are not sensitive to the assumptions about the nature of the overburden. Moreover, the properties of the overburden can readily be determined at a proposed disposal site.

---

[*] In hydrogeology, dispersion is defined as the spreading of a contaminant plume due to pore-scale velocity variations and macro-scale heterogeneity, combined with molecular diffusion. We assume, however, that the term is used here in a more generic sense, indicating distribution of radionuclides over a larger volume.

7. Did you take into account the borehole EDZ?

The excavation disturbed zone (EDZ; in the context of boreholes also referred to as a drilling disturbed zone, DDZ) is accounted for in the model. Its permeability is conservatively assumed to be higher than that of the surrounding rock by a factor of 100. Moreover, we assume the permeability of the DDZ is not reduced by grouting or other means during borehole sealing, nor by natural self-healing processes.

8. Can we derive any requirement (performance target) about the borehole sealing from the safety assessment itself?

Requirements can be derived from the safety assessment, even though factors other than the long-term repository safety may need to be considered. In general, a requirement for a repository component is formulated only if a specific barrier function has been assigned to that component, and barrier functions are only assigned if the component is necessary to assure repository performance, considering all features, events, and processes (FEPs) that need to be addressed, i.e., those FEPs that have sufficiently high occurrence probability and/or significant consequences. The FEPs addressed in our analysis include (a) a strong seismic event immediately after repository closure, (b) reactivation of faults that intersect the disposal section of the repository, (c) early failure of all canisters, (d) the presence of an overpressured saline formation below the repository, connected to an infinite supply of water, and (e) poor installation or failure of all plugs and seals in the borehole. The analysis shows that the consequences of such an unlikely combination of FEPs on peak dose are insignificant, i.e., that borehole sealing does not need to fulfill a barrier function for the repository to be safe. Based on this post-closure assessment, no requirements for borehole sealing need to be formulated. Nevertheless, sealing and backfilling the borehole is a sensible strategy also for reasons other than long-term safety, and may be needed to comply with existing regulatory requirements. Deep Isolation plans to properly plug, seal, and backfill the access holes of the repository.

9. Is there any difference between a well sealed and poorly sealed borehole, considering the gas migration (due to corrosion)?

We have not examined the behavior of gas in a poorly sealed borehole. However, preliminary simulations of corrosion gas generation indicate that the resulting gas saturation within the disposal section of the repository remains very small, mainly because of (a) relatively low volumetric density of corroding material; (b) high ambient pressures, which (i) keep hydrogen dissolved in the liquid phase, and (ii) result in relatively high gas-phase density; and (c) diffusion of dissolved gas away from the repository, which is promoted by the axial-radial geometry of a borehole. This low volumetric gas saturation is likely to lead to individual gas pockets rather than a continuous gas phase. Should a continuous gas flow path evolve, it would have a very low relative permeability. Also note that the period during which a free gas phase exists is relatively short. The disposal section of the repository can be drilled with a small incline, so should gas become mobile, it will flow toward the dead end of the repository rather than toward the vertical access hole. Because of these reasons, it is considered unlikely that a free gas phase could propagate along the borehole and reach the vertical access hole.

10. How is the poor sealing defined? Having no safety function at all? No retardation capacity? Based on the results, are requirements needed for sealing?

Poor borehole sealing is defined as follows. While the borehole assumed to be backfilled with some porous material, this material poses little resistance to fluid flow (it has a permeability of 1.0E-13 m^2, equivalent to a hydraulic conductivity of 1.0E-6 m/s or 100 millidarcy). This assumption makes the borehole the preferential flow path of least resistance between the disposal section and the near-surface aquifer. This high permeability could be attributed to a poor installation of a plug or seal, the chemical or mechanical degradation of the sealing material, and the existence or creation of gaps and fractures, specifically at the contact between the backfill material and the surrounding formation. Such weakening of the backfill is conservatively assumed to be present along the entire length of the borehole. Furthermore, these weaknesses are applied immediately after repository closure, and they are assumed to persist throughout the entire performance period (i.e., no closure, cementation, or other self-healing mechanisms take place). Finally, it is assumed that radionuclides do not sorb onto the backfill material, i.e., their transport is not retarded.
The results of the post-closure assessment show a negligible impact of sealing failure on repository performance. Consequently, no barrier function needs to be assigned to the borehole seal, and thus no requirements need to be formulated. However, Deep Isolation plans to properly plug, seal, and backfill the access hole of its borehole repository.

11. Does the outcome for this study apply only to horizontal boreholes or would it be the same or similar for vertical or slanted?

The outcome from the horizontal borehole study also applies to vertical or slanted boreholes used to dispose of nuclear waste. This is because the main reason why borehole leakage is insignificant is not related to the borehole orientation, but to the small cross-section of the borehole, the radial dissipation of pressure to the rocks surrounding the access hole, and the lack of mobile water or a sustained driving force. We are currently simulating the poorly sealed borehole scenario for a vertical borehole repository to confirm this.

12. Does a tight seal on the borehole increase the temperature of the borehole, and if so, is there a concern about the high temperature?

This is a two-part question:

(1) Backfilling the borehole will actually reduce the temperature within the borehole. The waste generates heat (initially about 1 kW per canister). The temperature in the borehole depends on how fast this heat can dissipate into the host rock by conduction. If the borehole were open and filled with water, the temperature of the canister would rise, because water has a relatively low thermal conductivity (of about 0.6 W/m/K), i.e., it acts as an insulator. Filling the borehole with clay or sand or rock or any of the other proposed backfill materials (which have thermal conductivities between 2 and 10 times that of water) will facilitate a more effective transfer of heat from the canister to the host rock.
(2) The expected temperatures in a borehole repository do not give rise to concerns. A borehole repository does not require people or machinery to work underground, the pressure is high, no boiling occurs, and no temperature-sensitive bentonite buffer is needed. Finally, the end-to-end arrangement of canisters, each holding a single spent nuclear fuel assembly, leads to a

relatively low heat-load density. As a result, the maximum temperature in the repository is only about 60ºC above the prevailing ambient temperature in the reference scenario.

13. If the casing is sealed from the formation via the annulus[*], why would the well[†] require sealing/plugging at all?

No long-term barrier function is attributed to the casing. Rather, the casing will be removed from the access hole prior to sealing the borehole to increase the effectiveness of the plugs and seals. The casing is needed to protect the aquifer during drilling and to facilitate the emplacement (and potential retrieval) of the canisters.

14. If you had an unsealed borehole, an uncollapsed borehole but with ruptured canisters, is it realistic to assume the local pressure in the waste disposal section is high enough to prohibit steam formation?

The borehole is always filled with water or brine at a pressure that is close to the hydrostatic pressure corresponding to the depth of the repository. For example, the fluid pressure in a borehole repository at a depth of 1.5 km is close to 150 atmospheres. The boiling temperature at this pressure is approximately 340ºC (650ºF), i.e., far above the maximum temperature that can be generated by the waste's decay heat. The pressure conditions are not affected by the state of the borehole or canisters. Therefore, no boiling will occur in a deep borehole repository.

Long-Term Safety Questions

15. Have you considered fault activation by the injection pressure in your simulation and the fault itself being the leakage pathway and not the sealed borehole?

Earthquakes and fault activation are not anticipated to be an issue with borehole disposal of spent nuclear fuel and other solid nuclear waste forms. By contrast, earthquakes and fault activation have occurred when waste fluids from hydraulic fracturing are pumped at high pressure into fluid disposal wells. It is also a concern for carbon sequestration, which involves pumping high-pressure fluids into rock. Deep Isolation will be disposing *solid* waste forms encapsulated in canisters, i.e., no fluid injection or associated pressurization will occur. Slight overpressures may be induced during over-balanced drilling, but no seismic events will be triggered, or faults activated due to drilling or any other repository operations. We considered faults (reactivated by strong, *naturally* occurring earthquakes) to be potential leakage pathways, making very conservative assumptions about their transmissivity, location and orientation, and inability to seal. These fault leakage effects are accounted for in our models; please see Deep Isolation's papers on the safety calculations (https://www.mdpi.com/1996-1073/13/10/2599/pdf) and borehole sealing (https://www.mdpi.com/1996-1073/14/1/91/pdf).

---

[*] The annulus is the space between concentric casing strings or between the outermost casing, and the borehole wall. It is typically filled with cement but may also be open, i.e., it does not necessarily act as a seal. We assume the question is about the casing itself serving as a seal between the hole containing the waste canisters and the formation.

[†] A well is used to inject or produce fluids. No such intentional, forced fluid flow occurs in a repository for nuclear waste. We therefore use the term “borehole” instead of “well.”

16. What can you say about the earthquake risk of radiation exposure to humans from deep borehole nuclear waste disposal?

No increased radiation exposure risks are expected as a result of earthquakes. There are two main potential consequences of earthquakes:

(1) *Direct effects during the earthquake.* The acceleration (shaking) during an earthquake is not expected to affect the integrity of the canisters. Such shaking is significantly smaller at the depth of the repository compared to the secondary surface waves we experience at the land surface. An earthquake may also reactivate an existing fault that intersects the repository (and has not been discovered during site characterization). If the fault offset is large enough, this may rupture one or a few canisters, leading to early releases of radionuclides (should the earthquake occur relatively shortly after waste emplacement). We have examined this "early canister failure scenario" using the conservative assumption that all canisters in the repository are damaged, and that the radionuclides are mobilized instantly without solubility limits and without retardation effects. The consequences of this very conservative scenario on repository performance is insignificant (see Section 6.2.3 in https://www.mdpi.com/1996-1073/13/10/2599/pdf), thus radiation exposure to humans from such an event is highly unlikely.

(2) *Indirect effects as a result of changes in the geosphere.* Faults reactivated during a large earthquake may become preferential leakage pathways for radionuclides from the repository to the land surface. We have examined multiple such scenarios, making the conservative assumptions that (a) the fault intersects the disposal section of the repository, destroying all canisters; (b) the fault is subvertical and extends all the way to the land surface; (c) the fault has a high transmissivity at its core and is surrounded by a zone of enhanced fracture permeability; (d) the fault remains "open" during the entire performance period, i.e., up and beyond the time when peak dose is reached (>1 million years); and (e) the fault taps into a large reservoir of pressurized water below the repository, which induces a continuous upward flow of water through the fault. While the exposure dose is somewhat affected by this conservative scenario, the effect is small and does not significantly influence repository performance. The probability of this scenario is expected to be very low. For details, please see Section 6.4 in https://www.mdpi.com/1996-1073/13/10/2599/pdf and the discussions in https://www.mdpi.com/1996-1073/14/1/91/pdf, which combine the seismic scenario with the additional conservative assumption that the borehole is poorly sealed.

17. Why do the figures not include metals[*] ?

The figures show the most safety-relevant radionuclide, which is I-129. This isotope has a very long half-life, a large inventory, high solubility limit, and low sorptivity, making it highly mobile. I-129 is the dominant contributor to the exposure dose, as confirmed by other safety analyses of repositories in shale formations. Radioactive heavy metals and their decay products will be included in a site-specific, comprehensive safety assessment.

---

[*] We assume the question is concerned with radioactive heavy metals, rather than non-radioactive metallic components of the canister and casing.

18. Are there any types of geological formations that you have determined would probably NOT be suitable for Deep Isolation?

A site that has a relatively permeable rock, with no tight host or cap layer, and evidence (determined by isotopic analysis) of upward flows, is unlikely to satisfy our isolation requirements. Resource conflicts, i.e., the presence of groundwater, hydrocarbons, or minable ores below the repository, also need to be avoided.

19. Do you have any calculation on the risk of accident (e.g., sucking or dropped canister)?

Deep Isolation has not yet calculated the pre-closure safety risks. We note, however, that nuclear handling operations to move SNF assemblies from fuel pools to dry casks are performed routinely. Similar operations and risks could be assumed for the transfer of the SNF assemblies into disposal canisters and to the repository site. Many risks associated with drilling as well as the lowering and retrieval of equipment into and from a borehole are well understood by the drilling industry, with effective mitigation measures in place. Deep Isolation examined various accident scenarios (e.g., canisters getting stuck or dropped). In compliance with strict NRC regulations, the canisters are being designed to be safe (have no leakage) if they are accidentally dropped onto a hard surface above ground. If they are accidentally dropped into a borehole, their velocity is limited by the resistance of the fluid (brine or drilling fluid) that fills the hole, making any impact less damaging than would be a surface drop.

20. You noted the high (relatively) permeability of the overburden to diffuse[*] out the plume. Is this feature relevant in leading to a small individual dose on the surface? So just that the case is not too analogous to dumping the waste into the ocean: max individual dose is small due to dilution. I presume symmetry boundary conditions should not allow the dose to "leak out" of your consideration, even if there is horizontal permeability? In any case, should one analyze the total dose to the biosphere in addition to the max single person?

Radionuclide releases from the repository (including the poorly sealed access hole) and their transport through the host rock is indeed diffusion dominated with the associated dilution effects. Transport in the overburden has a stronger advective component, partly induced by the pressure drawdown from the drinking water well. Symmetry boundary conditions are imposed, preventing undue dilution. Moreover (unlike in the case of dilution in the ocean) the drinking water well eventually collects *all* radionuclides released from the repository. Dilution in the aquifer is consistent with IAEA's assumptions about such effects and has been varied in our probabilistic safety analysis. The total releases to the aquifer and maximum concentrations within the aquifer are also tracked and have been reported (see, for example, Figure 4 in https://www.mdpi.com/1996-1073/13/10/2599/pdf).

21. Could you please look at disposing of conditioned residues (vitrified and compacted metallic, without fissile material)?

---

[*] We assume the term "diffusion" is used here as a generic term implying general redistribution of radionuclides, rather than the specific process of molecular diffusion. Note that permeability affects the advective (not diffusive) transport of radionuclides through the pore space.

A foundation study could look at disposal of a specific waste form. The study could include a cost analysis as well as a safety analysis for a specific type of waste and host rock.

22. Were over-pressurized domains considered in the safety assessment?

Over-pressurized domains are considered in our analyses. A sensitivity analysis on the impact of over- and underpressures on repository performance have been described for the nominal case in Section 6.2.2 of Deep Isolation's papers on the generic safety calculations (https://www.mdpi.com/1996-1073/13/10/2599/pdf). Specifically, it is assumed that the saline formation below the repository is overpressured and provides an infinite supply of mobile water, sustaining a general upward flow of water through the entire repository system, and, specifically, providing a driving force that pushes water along the reactivated faults into the poorly sealed disposal section and along the vertical access hole. Abnormal pressures are specific risks investigated in site characterization.

23. How are you sure that the water table* is not affected?

It is obviously very important that any repository system not have a detrimental effect on the biosphere, and specifically, groundwater aquifers that are used as sources for drinking water.

Deep Isolation's safety calculations evaluate the role of the repository's multiple barrier systems and the consequences should they be compromised. The generic analyses suggest that a deep borehole repository offers considerable passive safety, and can be placed at great depth, far removed from the water table and the impacts of dynamic processes at the land surface. The environment at depth is likely to be stable and can be demonstrated to have been out of contact with the groundwater aquifer for very long times. Even with engineered barriers present (specifically the waste form itself, which consists of solid pellets, and the waste canisters), our analyses indicate that the repository would be safe even if these barriers were breached immediately after repository closure.

In summary, the inherent, passive safety afforded by the deep borehole disposal concept, combined with site-specific analyses made with conservative assumptions and accounting for uncertainty, build the basis for the assessment that groundwater used for drinking water purposes will not be negatively impacted by the presence of the repository deep underground.

24. What's the Plan B in the case of failure and leakage of radionuclides through underground pathways into water supplies?

Deep Isolation will have to demonstrate a safety case through the licensing process. The safety case will require a detailed evaluation of "disruptive" scenarios and a description of how to address them. In fact, the safety assessment process starts with an exhaustive list of

---

*The "water table" is defined as the level below which the pores of the soil or rock are fully saturated with water. We presume the question is concerned more broadly with radionuclides entering a freshwater aquifer used as an underground source of drinking water, not just the interface between the saturated and unsaturated zone.

conceivable, adverse conditions – referred to as features, events and processes, or FEPs – and examines both the likelihood and consequences. The repository would be designed such that it meets the safety requirements (dose standard) even if such adverse events occur. Some impacts — even if unlikely or unpredictable — can be effectively mitigated.

25. If I understood your presentation, your analysis essentially assumes that eventually the radwaste will propagate into the host rock. Is your dose calculation essentially an estimate for this eventual material propagation?

The safety of a borehole repository is a direct result of its depth, which isolates and protects the canisters and the waste encapsulated in them behind a stable natural barrier system, which consists of the tight host rock and a thick overburden, where radionuclides are effectively confined or retarded. The main purpose of a safety calculation is to evaluate the performance of this multi-barrier system and to examine the consequences should it be breached. Should radionuclides be released, they would be transported by groundwater flow and diffusion into the host rock and from there through the overlying formations. This transport is expected to be very slow, leading to very long travel times during which most of the radionuclides decay, either within the canister, in the repository's near field, or along the migration pathway. Deep Isolation's analysis shows that the safety of a deep borehole repository is not compromised by the potential degradation of the borehole seals.

26. Is a higher permeability overburden a requirement in site selection, since this was key to the mitigation of borehole transport up the borehole?

The permeability of the overburden is indeed assumed to be relatively high compared to the very tight formation selected as the host rock; the chosen permeability is representative of typical overburden formations (e.g., carbonates, marls, sandstones, shales).

The loss of radionuclides from the borehole into the surrounding overburden by flowing groundwater (referred to as advective transport) is only one of several effects that help reduce the upward migration of water and radionuclides along the access hole, making leakage through the access hole an insignificant contributor to the total radiological exposure dose. Even if advective losses were small, radionuclides still enter the overburden by diffusion, and the borehole's small cross section combined with the difficulty to sustain a driving force over its entire length further reduces its potential impact. The effectiveness of radial losses can be examined for the site-specific properties of the overburden, which can readily be determined as part of site characterization. Should the overburden indeed have a "host-rock-grade" permeability, the repository would most likely be very safe even if radionuclide fluxes through the access hole may be slightly higher during a disruptive event.

27. What is the next most limiting radionuclide after I-129?

In Deep Isolation's generic safety calculations, which are summarized in https://www.mdpi.com/1996-1073/13/10/2599/pdf, I-129 is the dominant contributor to the total exposure dose, followed by Se-79 and Cl-36. This list of safety-relevant radionuclides is consistent with the radionuclides emerging as the main dose contributors in other, comprehensive safety analyses that look at repositories in shale formations. A site-specific safety assessment will include most or all radionuclides present in the waste form as well as their safety-relevant decay products.

28. Models are great — your model shows that even with failure it still works. However, confidence might be built if you conduct material studies between the host rock and the backfill material under varying environments — i.e., high heat, high pressure, etc. Does Deep Isolation intend to conduct material studies?

Numerical models are most useful to improve system understanding, to test hypotheses, to examine what-if scenarios, to identify relevant features, parameters, and processes, and to get bounding values and uncertainty ranges. The usefulness of a model must be critically evaluated, accounting for its intended purpose. The conceptual model and the input parameters should be based on experimental studies, field observations, and insights gained from natural analogues, accounting for the fact that these parameters may be conceptually (and thus numerically) different from measured values.

Backfill materials and their interactions with the surrounding geological formations have been studied in great detail, specifically in the context of nuclear waste isolation. These studies range from theoretical investigations to laboratory experiments and to field tests. Deep Isolation has access to the findings of such studies and can use them for the site-specific designs of plugs, seals, and backfills of its boreholes; we agree that they are helpful in analyzing the suitability of the host rock.

Monitoring Questions

29. What are the available monitoring technologies for leakage?

The available monitoring technology for leakage detection depends on the time frame and location where such monitoring is employed. During the operational (pre-closure) phase, potential leakage through the access hole can be measured by monitoring pressures, temperatures and radiation levels as indications of, respectively, the presence of an upward driving force, bulk fluid movement, or radionuclide transport. Similar quantities can be monitored during the post-closure phase (e.g., pressure and radiation measurements on either side of a plug sealing the mouth of the waste disposal section; sensors placed in observation holes *above* the repository's sealing formation; monitoring of groundwater quality; geophysical imaging; thermal heave at the surface). However, the repository's post-closure safety performance must satisfy regulatory requirements without relying on monitoring and remedial actions by future generations, even though mitigation might be possible (e.g., by monitoring, treating, or discontinuing the usage of a source of drinking water affected by radionuclides).

Heat Questions

30. What was the assumed heat load in each borehole? (You indicated that heat load was high). Dry casks are typically loaded with to 25 to 45 kilowatts (but this decays over time).

The heat emitted is a function of time (see Figure 2 in Deep Isolation's paper https://www.mdpi.com/1996-1073/12/11/2052/pdf). For the disposal of commercial used fuel from a pressurized water reactor (PWR) with an initial enrichment of 4.73%, a burn-up of 60 GWd/MTIHM, and a cooling time of 30 years, the heat output is approximately 625 watts per canister at the time of disposal, 250 watts per canister after 100 years, and 25 watts per canister after 1,000 years. Unlike in a dry cask, the heat-generating assemblies are emplaced in a borehole in a linear, end-to-end configuration, which results in a low volumetric heat density and high conductive heat-dissipation capacity. As a result, the temperature rise in the repository is moderate, with a peak value considerably below 100ºC (212ºF), which occurs a few decades after repository closure and is followed by a steady decline in temperatures.

31. How much heat is being generated in a sealed repository over what period of time? Is heat expected to draw water to the repository?

Deep Isolation’s safety assessment models account for the decay heat generated by all radionuclides present in spent nuclear fuel from a commercial pressurized water reactor (PWR) with an initial enrichment of 4.73%, a burn-up of 60 GWd/MTIHM, and a cooling time of 30 years. The heat emitted is a function of time (see Figure 2 in Deep Isolation's paper https://www.mdpi.com/1996-1073/12/11/2052/pdf), with approximately 625 watts per canister at the time of disposal, 250 watts per canister after 100 years, and 25 watts per canister after 1,000 years. This thermal energy readily dissipates into the surrounding host rock by heat conduction, leading to only moderate temperature increases in the repository.
Heat is not expected to draw water toward the repository; by contrast, the temperature increase leads to a slight expansion of the water, which is being push outward, preferentially along the borehole. However, this outward flow is minor because of the small expansion coefficient of water and the simultaneous expansion of the pore space due to temperature and pressure changes.

32. How is the decay heat safely removed from the canister before and after it has been sealed? Is it shaft ventilation?

Borehole disposal does not rely on active ventilation. Note that the borehole is filled with drilling or completion fluids or brine from the formation. Decay heat dissipates through these fluids into the surrounding host rock by thermal conduction without causing drastic temperature increases within the borehole. Moreover, the heat-generating assemblies in a borehole are placed in a linear end-to-end configuration, which results in a low volumetric heat density and high conductive heat-dissipation capacity.

By contrast, ventilation is necessary in a mined repository to keep temperatures sufficiently low so people and machinery can work underground during characterization, waste emplacement and repository closure activities. No such constraints exist in a borehole repository.

33. What is the likely ambient temperature in the host rock without the repository?

For an average geothermal gradient of 30ºC/km (15ºF/1,000 ft) and an average temperature at the land surface of 15ºC (60ºF), the ambient temperatures for a borehole repository at a depth of 1, 2, and 3 km (3,300, 6,600, and 10,000 ft) are approximately 45, 75, and 105ºC (115, 170, and 220ºF), respectively. These values can easily be scaled to site-specific conditions.

Canister Questions

34. Influence of canister material in calculations?

The canister material has no influence on the calculations presented in https://www.mdpi.com/1996-1073/14/1/91/pdf. Canister materials mainly influence the corrosion rate and thus the time of canister breach and initial radionuclide releases. In our calculations, we made the assumption that all canisters are breached immediately after repository closure due to the impact of fault reactivation caused by a strong earthquake. Even though such an early canister failure scenario is highly unlikely, it was chosen to highlight the role of borehole sealing.

35. Containers holding high-level nuclear waste eventually leak. Unknown pathways might allow the waste back to surface.

A borehole repository provides a considerable level of passive safety, specifically because of its depth, which removes the waste from perturbations at or near the land surface. This in turn creates long migration distances and long travel times, which allow radionuclides to decay. Moreover, canisters are arranged in a linear configuration, which results in a comparatively small waste density. Repository safety will be evaluated based on detailed site characterization and diligent performance assessment that examines the probability and consequences of a large number of conceivable, adverse features, events, and processes (FEPs).

These analyses indeed consider the case that the radionuclides leak out of the canisters, and that unknown preferential pathways (such as undetected or reactivated earthquake faults) exist, or that the seals of the access hole degrade, generating a preferential flow path. In a bounding calculation, such pathways and related failure scenarios are conceptualized such that their consequences on repository performance are potentially large. Nevertheless, our generic analysis indicates that radionuclide releases to the biosphere through such potential (known or unknown) pathways do not significantly increase the exposure dose, confirming the effectiveness and robustness of the passive safety features of the borehole repository.

Retrievability Questions

36. What are the prospects for retrievability of stored fuel once placed in storage?

Our goal is to make retrieval feasible using a robust and safe approach. The disposal canister has a special connector at its back end to allow latching to the placement cable, unlatching, and relatching for retrieval. This system has proven its reliability in the oil and gas industry, but redundancies will be built in to provide backup if the primary latching mechanism fails. Deep Isolation conducted a demonstration in 2019 in which a canister was placed in a horizontal section of a borehole, released it, withdrew the cable and latching mechanism, reinserted it several hours later, and retrieved the canister. Such retrievals are routinely performed in the oil and gas industry, and there are even special “fishing” techniques that would allow retrieval if both of our redundant methods fail. Deep Isolation conducted a demonstration in 2019 in which a canister was placed in a horizontal section of a borehole, released it, withdrew the cable and latching mechanism, reinserted it several hours later, and retrieved the canister.

37. What are the prospects for retrievability of stored fuel once placed in disposal*?

Our goal is to make retrieval feasible using a robust and safe approach until the vertical access hole is sealed. After borehole sealing, retrievability could still be possible, although requiring increased effort, which is consistent with the waste being in disposal (rather than in storage). In the case of post-closure retrievability of disposed waste, the backfill in the access hole must be removed, or a new borehole must be drilled that intercepts the disposal section. The disposal canister has a special connector at its back end to allow latching to the placement cable, unlatching, and relatching for retrieval. We are using a system that has proven its reliability in the oil and gas industry, but we are putting in special redundancies to provide backup if the primary latching mechanism fails. Such retrievals are routinely performed in the oil and gas industry, and there are even special "fishing" techniques that would allow retrieval if both of our redundant methods fail.

Deploying the Deep Isolation Solution

38. How many fuel assemblies were assumed in each borehole in your model?

In these generic safety calculations, we assumed that the disposal section of each borehole is 1 km long, which accommodates 153 waste canisters, each containing a single spent nuclear fuel assembly from a pressurized water reactor (PWR).

39. What is the amount of waste volume that can be stored in a single boring?

It depends on the length of the borehole (here assumed to be 1.0 km, but the disposal section could be longer) and length of and spacing between the canisters. For our safety calculations, we used 153 canisters with one PWR assembly per canister in each borehole. About 20 boreholes of this size are needed to dispose of the spent nuclear fuel generated by a 1GW reactor over its lifetime.

40. To what extent have the effects of multiple boreholes in close proximity been evaluated? Is there a minimum recommended distance between adjacent boreholes or a cluster of boreholes?

---

*The term "storage," which refers to the temporary placement of nuclear waste in a safe location with the intent to retrieve it prior to closure of the facility, must be distinguished from permanent "disposal" with no intent to retrieve after closure. Boreholes may be suitable for both the storage and disposal of nuclear waste.

The model accounts for the interaction effects of multiple boreholes that are assumed to be drilled in parallel with a separation distance of 100 m. Notably, the effects of a limited rock volume available for diffusive dilution is accounted for. Thermal interference effects are also accounted for, but they are inconsequential. As a first approximation, the peak exposure dose increases are inversely proportional to the separation distance between the boreholes. This means that the separation distance can be used as a design parameter to control repository performance.

41. Performance confirmation occurs during construction and operation and supports the decision to close the repository. What activities could be completed as a part of a performance confirmation program for a deep borehole repository?

A performance evaluation program would be established and conducted during operations up through the end of the pre-closure period (end of any required retrievability). The regulator would authorize the closure activities once it is assured that performance is as anticipated. A post-closure performance evaluation program could be conducted as necessary to satisfy any license conditions.

42. What activities could be completed as a part of a performance confirmation program for a deep borehole repository?

Potential leakage through the access hole could be measured by monitoring pressures, temperatures and radiation levels as indications of, respectively, the presence of an upward driving force, bulk fluid movement, or radionuclide transport. Data collected during the performance confirmation period would be analyzed to evaluate whether the repository system performs as intended. A site-specific safety assessment will include most or all radionuclides present in the waste form as well as their safety-relevant decay products.

43. Has the Deep Isolation team considered the potential for movement into a cavern — either undiscovered or newly-created? What can be said of such a case leading to the potential for establishing a critical configuration[*] for stored[†] spent fuel?

The site characterization process should determine if there are areas that could create caverns through salt dissolution or other engineering methods or natural processes. Any such formations would be excluded.

44. Approximately what percentage of the existing commercial nuclear power plant sites in the United States have sufficiently tight host rock at 1.5 km to accommodate this technology?

---

[*] The term “critical configuration” refers to an accumulation of fissionable material that could sustain a nuclear chain reaction.

[†] The term “storage”, which refers to the temporary placement of nuclear waste in a safe location with the intent to retrieve prior to closure of the facility, must be distinguished from permanent “disposal” with no intent to retrieve after closure. Boreholes may be suitable for both the storage and disposal of nuclear waste.

Based on large-scale maps of shale or nearer surface granite formations, it appears that a majority of nuclear power sites may have suitable geology at or near the plant for a potential site. Detailed site-specific reviews would need to be done on a case-by-case basis for each potential site to verify any large-scale information.

45. How does borehole storage or disposal correlate to the average amount of waste at a single nuclear power plant? Will multiple borings be needed at a given plant?

The average nuclear plant will need between 10 and 20 boreholes depending on the size, type of fuel, duration of operation and length of borehole.

46. Pros and cons of consolidating to a larger storage footprint with multiple boreholes vs. distributed at multiple facilities?

Pros of one facility is that you have one site to characterize, license and build infrastructure on so there could be some cost efficiencies. An example could be a repackaging facility at the consolidated disposal facility. The facility could take SNF from multiple locations and package it into disposal canisters. This facility could be very expensive and could provide benefits to consolidating all operations through one facility.

Cons for one facility is that some waste will be transported long distances, and there is a single point of failure for a national repository system if there is a mechanical breakdown at the facility.

47. What will determine when and where you will begin making Deep Isolation nuclear waste internment?

The answer to both when and where a Deep Isolation solution will be realized is dependent upon a convergence of multiple factors. Key among these will be the license required for the disposal of the spent fuel, and a partnership with a community to host the site. It will be a step-wise process to site, license, build and operate the facility.

48. Can Deep Isolation hazard any approximate time frame for starting actual nuclear waste disposal operations?

Many of the technologies that would be employed are available today. These include horizontal drilling, emplacement tools, and nuclear handling methods. However, each potential disposal site would need to be characterized and licensed for the specific waste inventory, and the timeline will be dependent upon a convergence of multiple factors, including establishing a partnership with any community that serves as a host for a disposal facility. It will be a step-wise process to site, license, build and operate such a facility.

49. Is the horizontal section cased and cemented before running the spent fuel containers?

The entire borehole is cased, and the casing is cemented in place, mainly to facilitate the emplacement — and potential retrieval — of the waste canisters. However, as part of the closure activities, the casings in the access hole will be pulled (with the exception of the section that intersects an aquifer) and the borehole will be plugged, sealed and backfilled.

50. Host rock may be shale?

The host rock may be shale but various types of formations are also suitable as potential host rocks for a borehole repository. The analysis presented in this webinar is based on shale as a host rock, or another argillaceous formation, i.e., a sedimentary rock that contains clay. We also looked at generic basement rocks (i.e., fractured, igneous or methamorphic rocks). Site characterization will assess the benefits and limitations of potential host rocks and their overburden.

51. You always talk about "the access borehole" but show many horizontal boreholes. Could a multitude of vertical boreholes not in the end be as conductive as a two-dimensional fault (depending on the assumed transmissivity of the borehole and the fault)? Do you want to drill only one (vertical) access borehole and many horizontal ones from that?

Our analysis considers not only a single borehole, but an array of boreholes, whereby each horizontal disposal section of the repository hole is reached by its own vertical access hole. In our analysis, the potential leakage through *multiple* access holes is properly accounted for. Nevertheless, faults are both geometrically and hydraulically much bigger structures (by multiple orders of magnitude). As suggested, one might consider developing multiple horizontal waste disposal sections emanating from a single vertical access hole. The post-closure analysis shows that having multiple vertical access holes does not compromise the long-term safety of the repository. It should also be noted that there are some drilling challenges and potential risks during the emplacement of waste into a multi-lateral system, where several horizontal disposal sections emanate from a single vertical access hole. Nevertheless, if these risks are properly managed, the decision to use just a single access hole can be driven by cost considerations and available space at the land surface.

52. Is this type of disposal suitable for HLW disposal?

It is technically possibly to dispose of HLW canisters in a borehole. It does depend on the size of the waste canister, which may be larger and would therefore require larger diameter boreholes. There are many examples of larger diameter extended-reach well bores in offshore environments, where they are more appropriate for resource extraction. Studies by our drilling technical advisor show that large deep horizontal boreholes (45cm) are feasible in appropriate host rock formations using ‘off the shelf’ drilling and casing technologies. Industry specialists expect that specialty 57 cm casing for horizontal boreholes will be available shortly.

53. Why is horizontal drilling necessary? Why not just vertical? How about drilling in the ocean at subduction locations?

Deep Isolation has not pursued the option of disposal in or near oceanic subduction zones.

The orientation of the waste disposal section (horizontal, vertical, inclined) can be considered a design option rather than a necessity. Each orientation has its site-specific advantages regarding access to a suitable host rock, drilling and waste emplacement, pre- and post-closure safety, costs, etc.

For example, horizontal boreholes have some safety and economic benefits. For example, they provide access to shale formations that tend to have considerable horizontal (but more limited vertical) extent. Horizontal drilling in such formations has been demonstrated to be cost-effective, as generally fewer geological contacts with changing properties need to be drilled through; canisters are emplaced without accumulating stacking loads; the waste disposal section is off-set from the vertical access hole and perpendicular to more critical vertical driving forces, providing some additional passive safety; horizontal drilling could provide access to marine sediments from a drilling rig on dry land; etc.

Horizontal boreholes have some safety and economic benefits. For example, they provide access to shale formations that tend to have considerable horizontal (but more limited vertical) extent. Horizontal drilling has been demonstrated to be cost-effective, as generally fewer geological contacts with changing properties need to be drilled through; canisters are emplaced without accumulating stacking loads; the waste disposal section is off-set from the vertical access hole and perpendicular to more critical vertical driving forces, providing some additional passive safety; potentially very long horizontal disposal sections could be drilled, accommodating more canisters per borehole; horizontal drilling could provide access to marine sediments from a drilling rig on dry land; etc.

Legislative and Regulatory Matters

54. How should generic disposal/repository standards by the EPA, NRC, and DOE change?

The latest regulatory standards for geologic disposal published by NRC and EPA are risk-informed and performance-based. Existing standards, such as 10 CFR Part 63, are focused solely on Yucca Mountain, however. Generic repository standards included in 10 CFR Part 60 are more dated and function more like a checklist of attributes instead of how the system works as a whole. The Part 60 regulatory framework is generally considered to be obsolete. New regulatory standards will be required for borehole disposal because there are no standards currently in place that would be applicable to borehole disposal. Coordination between EPA, NRC and the DOE will be necessary.

55. How would you collect the information necessary to describe the barrier[*] and its capability required by NRC regulations?

It is relatively straightforward to describe, characterize, test and monitor the sealing capability of a borehole plug or seal, specifically during the pre-closure performance evaluation period. For example, pressure tests and in-borehole tracer tests can be used to examine the tightness of a plug (including the surrounding drilling disturbed zone). Pressures, temperatures and radiation levels can be monitored as indications of, respectively, the presence of an upward driving force,

---

[*] Multiple engineered and natural barriers are in place. We focus our reply on the potential barrier function of the borehole seal, as this was the topic of the webinar.

bulk fluid movement, or radionuclide transport. Our analysis of borehole plugging suggests that no specific barrier functions need to be assigned to the borehole seal.

56. I would like to know what U.S. authorities like FERC have to say about Deep Isolation's concept.

The Federal Energy Regulatory Commission (FERC) is an independent agency that regulates the interstate transmission of electricity, natural gas, and oil. FERC does not have a regulatory role in nuclear waste disposal.