Safety Calculations Q&A

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This document serves to respond to public comments regarding the Safety Calculations report received by Deep Isolation on May 12, 2020, during a recorded webinar titled “Safety in Depth: Calculations for a Deep Horizontal Drillhole Repository (U.S.).”

In this webinar, Deep Isolation shared the initial results from the post-closure safety calculations for a generic deep horizontal borehole repository. This initial report was designed to analyze performance for the period of time after the repository has been closed and assumes that all canisters were successfully emplaced. Generic calculations are a valuable and necessary step in developing a safety analysis approach that will eventually support the safety assessment of a deep horizontal borehole repository. The report is titled “Spent Nuclear Fuel Disposal in a Deep Horizontal Drillhole Repository Sited in Shale: Numerical Simulations in Support of a Generic Post-Closure Safety Analysis” and will be referred to in this document as “Safety Calculation Report.”

The names of individuals asking questions have been excluded from the final document for privacy reasons.

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

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Pre-closure Questions

1. Q: Is there any reason that Deep Isolation conducted this safety assessment with a 1 km borehole instead of a very deep borehole (several kms)? Why is the repository in the transition zone of salinity and not in the saline zone?

   A: While a generic safety calculation may examine a wide variety of assumptions and parameter values, we felt it was necessary to limit the analysis to a single, illustrative repository design. A depth of 1 km was chosen to examine the safety function that the depth itself may fulfill — without selecting an extremely deep repository, which would not have been as conservative an approach. Note that the results for a repository at the depth of 1.5 km are discussed as a sensitivity case in Section 4.7.3.4 of the Safety Calculation Report. Similarly, we decided to include the effects of density stratification due to salinity but at the same time did not want to focus on the non-conservative case where the repository is placed in a deep, high-density brine. The effects of salinity on canister integrity are indirectly accounted for by choosing a (conservatively) high corrosion rate.

2. Q: The model assumes parallel alignment of the horizontal portion of the borehole. Would you anticipate any significant differences if the horizontal legs were oriented radially from a central point instead?

   A: There is considerable flexibility in the potential layout of the repository, including parallel, radial, sectoral, vertically staggered, from a central drill pad or multiple drill pads, following stratigraphic units, accounting for orientation of stress field, etc. A radial design may have certain advantages over a parallel design (e.g., less concentrated source term and thus potentially lower dose; drilling of fewer access holes; smaller surface footprint), but may also have disadvantages (e.g., waste emplacement and retrieval operations; inability to align with the orientation of stress field). The repository layout will be optimized for the conditions encountered at a specific site.

Siting

3. Q: What are your site selection criteria? In particular, driving forces and flow paths (heads, hydraulic gradients, distance etc.).

   A: Deep Isolation is in the process of establishing requirements for a suitable candidate site. Ultimately, safe isolation of waste can be achieved by multiple combinations of complementary and redundant safety features of the total repository system, i.e., the required properties of each repository subcomponent are site-specific. Nevertheless, some general criteria can be stated, such as: geologic stability; the age of the water in the disposal horizon; the isolation of the water at the disposal horizon from water above and below; geochemical conditions that favor the preservation of engineered barriers and promote geochemical immobilization or retardation of radionuclides along their migration path toward the receptor; and long radionuclide transport times from the disposal section to the accessible environment. All of these technical and regulatory requirements are necessary, but a primary element to successfully selecting a site is community acceptance. This is an earned achievement which we plan to accomplish by working closely and collaboratively with any potential host community.

4. Q: What is the hydrogeological data you need for a site assessment, and how can you obtain this? Kf values for shale are not easy to determine with just one or two orders of magnitude accuracy.

   A: Site characterization needs for a deep horizontal borehole repository are similar to those of any other disposal concept. We can rely on well-established characterization methods used in other nuclear waste isolation programs, as well as the methods used in the oil, gas and geothermal industries, geological carbon sequestration projects, resource exploration and other areas in geosciences. Note that many of these characterization methods are borehole-based. The impact of residual uncertainties in some key factors (such a shale permeability) must be accounted for when defining performance requirements for the related barrier component. However, our sensitivity and uncertainty analyses indicate that the performance metric (maximum radiological exposure dose) can be calculated with sufficient accuracy to obtain useful insights despite assuming a wide uncertainty range of the model's input parameters, including the determination of permeability, *K*. While we will rely on our ability to determine site-specific property values with sufficient confidence, we also rely on inherent safety features of the concept (such as depth, limited intrusion and perturbation of the host rock environment, geometrical features and other design factors).

5. Q: How will the permeability of the overburden rock be measured? How do we ensure a low enough permeability to prevent an aggressive upward advective transport?

   A: Permeability is routinely determined using geophysical and hydrogeological methods, many of which were developed from logging and testing in boreholes. Moreover, direct measurements of natural radioisotopes would give an indication of the age of the pore water and thus whether a significant advective transport component should be expected. Also note that we used a relatively high vertical permeability of 10^{-15} m^2 (1 millidarcy, or 10^{-8} m/s) for the overburden and actually see an advective transport component. Nevertheless, the other features of the deep horizontal borehole repository concept (depth, host rock, geometry, etc.) do not render such a relatively permeable overburden unsafe.

Questions about Long-Term Safety after Repository Closure

6. Q: One earthquake fault may not matter, but would unidentified fractures serving as preferential pathways be a concern? Would subsurface characterization be essential?

   A: In the preliminary safety calculations, we assumed that all geological formations, including the shale host rock, have relatively high permeability (compared to permeabilities used in other safety analyses for repositories in clay-containing formations). We chose a conservatively high, large-scale effective continuum permeability to include the potential presence of fractures, which may induce some advective groundwater flow and radionuclide transport.

In addition to conventional site characterization data about fractures and other water-conducting features, measurements of concentrations and gradients of naturally occurring, highly mobile radioisotopes, specifically chlorine, iodine and noble gases, provide information about the long-term isolation of the pore fluids and the long-range interconnectivity of the fracture network.

7. Q: Why do you assume that fluids in the shale host rock are overpressured? What are the implications of overpressure for fluid mobility, hydrofracturing and boiling temperatures?

   A: We do not assume the fluids in the host rock are overpressured; we assume they are close to the hydrostatic pressure, which is frequently the natural state of a saturated formation at depth. Hydrofracturing would only occur if a process existed that raised the pressure high enough so that the effective stress exceeded the minimum principal stress. As there is no fluid injection associated with nuclear waste disposal, and thermal fluid expansion is insufficient to lead to significant overpressures, no plausible scenario exists that would lead to conditions that initiate hydraulic fracturing. The hydrostatic pressures at depth prevent water from boiling until very high temperatures are reached.

   However, we do assume that the underlying saline formation is overpressured. This is a conservative assumption, as it induces an upward hydraulic gradient and thus the upward flow of brine. This brine could pick up radionuclides released from the repository and transport them via advection toward the drinking water aquifer near the land surface. If there were no advective radionuclide transport or the fluid flow were downward (i.e., by an under-pressured saline formation) rather than upward, the maximum annual exposure dose would be considerably smaller, as shown in Section 4.7.3.3 of the Safety Calculation Report.

8. Q: Will you be tracking temperatures, what temperatures do you expect, and what is the rate decline in temperature over time?

   A: Natural geothermal gradients and repository induced temperature effects are described in the Safety Calculation Report. Horizontal boreholes are relatively cool, typically 40-60°C at depth, with an additional temperature rise of about 30-60°C from waste heat during the first decade. Our safety calculations modeled the maximum temperature encountered in the repository area during the thermal period as slightly less than 100°C, which is well below the boiling point of water at that depth. After 1,000 years, the temperature is approximately 10°C above the ambient temperature.

9. Q: Is the modeling based on high burnup spent fuel? How would results be impacted for fuels with much higher burnup and decay heat than LWR fuel, e.g. 200MWd/kg versus 50MWd/kg?

   A: The Safety Calculation Report considers commercial PWR spent fuel with an initial enrichment of 4.73 percent, burnup of 60 GWd/MTHM, and a cooling time of 30 years. The safety of disposing of spent fuel with different initial enrichments, burnup, or cooling times can be assessed by specifying the appropriate radionuclide inventory and thermal output function in the model. We have not modeled higher burnup fuel. We expect temperatures to be higher but well below the boiling point of water under in situ pressure conditions.

10. Q: Have you modeled disposal of fuel that has just come out of the reactor or has just been cooling for five years in the onsite pools?

    A: We have not modeled this specific scenario. However, the main effect of short cooling time is the enhanced thermal output, which would lead to higher temperatures during a very short period immediately after repository closure. Note that other factors also affect the temperature evolution, including the radionuclide inventory, initial enrichment, burn-up rate, and also canister spacing and thermal properties of the host rock. Such simulations are therefore best done once the site-specific properties and the waste form have been sufficiently characterized. Finally, Deep Isolation has published a journal article that looks in more detail at thermal issues, albeit for a different waste form (see Finsterle, S., R.A. Muller, R. Baltzer, J. Payer, and J.W. Rector (2019): Thermal evolution near heat-generating nuclear waste canisters disposed in horizontal drillholes, *Energies*, *12*(4), 596, doi: 10.3390/en12040596).

11. Q: Will the boiling curve also apply before the closure of the borehole?

    A: Yes, the boiling curve is applicable because the borehole is filled with fluids throughout the pre-closure period, which includes drilling, waste emplacement, potential retrieval and repository closure operations. The pressure is close to hydrostatic during these operations, e.g., far above atmospheric, and thus the boiling temperature is very high.

12. Q: Please describe the peer review your work has undergone, or that you have planned.

    A: The Safety Calculation Report has been reviewed internally by Deep Isolation, by members of its Advisory Committee, and by external, international reviewers with considerable expertise in safety analyses. Moreover, the report is publicly available, and Deep Isolation solicited and received a number of review comments from interested parties. Finally, the approach and results of the safety calculations have been published in a peer-reviewed journal article (Finsterle et al., *Energies*, *13*, 2599, 2020: Post-closure safety calculations for the disposal of spent nuclear fuel in a generic horizontal drillhole repository), as well as three additional articles describing the Deep Isolation concept: (Muller et al., *Energies*, *12*, 2052, 2019: Disposal of high-level nuclear waste in deep horizontal drillholes), thermal calculations (Finsterle et al., *Energies*, *12*(4), 596, 2019: Thermal evolution near heat-generating nuclear waste canisters disposed in horizontal drillholes) and calculations of canister corrosion rates (Payer et al., *Energies*, *12*(8), 1491, 2019: Corrosion performance of engineered barrier system in deep horizontal drillholes). We welcome any comments and provide written responses and will consider addressing them in our future work.

13. Q: Can you give examples of changes made to the Safety Calculation Report as a result of outside feedback?

    A: We received external reviewers' suggestions to analyze specific scenarios that they consider potentially safety-relevant, including low-probability scenarios. We have analyzed some of these scenarios proposed by outside experts, or formulated our own additional sensitivity cases based on reviewer comments. We will continue to do so as part of the continuous process of refining the analyses as we further develop the Deep Isolation repository concept.

14. Q: How do these migration calculations match up with those found in the natural reactors at Oklo (Gabon, Africa).

    A: Oklo is a natural analog for the long-term behavior of fission and activation products, including: fuel stability under reducing conditions; isolation and retention capacity of clay minerals, oxyhydroxides, iron, phosphates and graphite; criticality; and hydrolysis, among other issues. No formal comparison has been made, as such a comparison would greatly depend on the assumed geochemical environment. In general, the abundance of uraninite and the distribution of radionuclides around the natural reactors at Oklo suggest that degradation rates and transport velocities are many orders of magnitude lower than what was conservatively assumed in Deep Isolation's generic safety calculations. If conditions at an actual Deep Isolation disposal site are comparable (or scalable) to those at Oklo, this natural analog can be included in the Safety Case, providing independent evidence about the long-term behavior of a high-activity waste repository.

15. Q: How is permeability structure in near and far-fields modeled? What type of permeability did you use for the shale in the repository section?

    A: Appendix B of the Safety Calculation Report contains a complete list of the permeabilities of all natural and engineered materials represented in the model. Most importantly, the anisotropic permeability of the shale is 10^{-17} m^2 in horizontal and 10^{-18} m^2 in vertical directions, respectively. In the probabilistic analysis, we sample these permeabilities in a range with bounds that are two orders of magnitude lower and higher than these base-case values.
    It is worth mentioning that this reference permeability is cautiously selected to be relatively high compared to the permeability used in other nuclear waste programs that look at clay formations. For example, the Opalinus clay in Switzerland has a permeability that is lower than our reference permeability by a factor of at least 1,000; the Boom clay in Belgium is 100 times tighter, and the reference permeability Sandia used for their analyses of shale disposal in the U.S. is also based on a value 100 times lower.
    The overburden also has a relatively high permeability of 10^{-14} m^2 in horizontal and 10^{-15} m^2 in vertical direction. The excavation disturbed zone around the borehole has an axial permeability that is higher by a factor of 100 than the formation the borehole segment is embedded in. The backfill and cement materials used in the borehole have a conservatively high permeability of 10^{-16} m^2. The canister and casing are initially impermeable, but their permeability increases to 10^{-16} m^2 (reflecting the permeability of the corrosion products) at the time they are perforated due to corrosion.

16. Q: In the source term, are all the canisters assumed failed in all the boreholes in the calculations? Do they all fail at the same time (common mode failure)?

    A: In the reference scenario, all canisters are assumed to fail at 10,000 years. In the early-canister-failure and instant-waste-mobilization scenarios, all canisters are assumed to fail immediately after repository closure.

17. Q: In the source term how many equivalent PWR fuel assemblies are assumed initially released to the near field?

    A: In the reference scenario, radionuclides initially encapsulated in all 153 PWR assemblies present in a 1-km-long disposal section are assumed to be released according to a fractional waste degradation rate (with a conservatively high rate of 10^{-5} per year). In the instant-waste-mobilization scenario, the radionuclides from all 153 assemblies are assumed to be instantaneously released at time zero.

18. Q: You had mentioned an instantaneous release of radionuclides. Could you go into that in more detail? Do you have any data on an instantaneous release?

    A: We looked at multiple issues related to the source-term model:

    (1) We examined higher and lower waste degradation rates based on data published in the literature;
    (2) We accounted for an instant release fraction of 20 percent for iodine; and
    (3) We performed a bounding calculation in which we assumed that (i) the canisters and casing corrode instantly, (ii) the waste form degrades instantly and releases all radionuclides instantly, and (iii) they dissolve fully and instantly in the pore water without a solubility limit.
    The results of this "instant radionuclide mobilization scenario" indicate that the details of the temporal release of radionuclides do not significantly influence the maximum dose value, i.e., residual uncertainties in corrosion and waste degradation processes do not have an undue effect on the results of the safety calculations.

19. Q: What difference might you see if the SNF in the deep borehole were replaced with HLW from the recycling of spent nuclear fuel?

    A: Our generic safety calculations consider SNF from a commercial PWR. Other waste forms are considered suitable for disposal in horizontal boreholes, and separate safety calculations would be performed for each.

20. Q: The modeled case assumes no coupled geochemistry or geomechanics, which is necessary to develop a "base case." However, is that realistic? Are there modeling capabilities that show geomechanical effects on thermal, fluid and radionuclide behavior or transport? Can you share your thoughts on those impacts in real-world scenarios?

    A: Geochemical and geomechanical processes have a potentially important impact on repository performance and thus need to be studied in detail. While simulation capabilities exist that can handle coupled thermal-hydrological-mechanical-geochemical (THMC) processes, such simulations are conceptually and computationally very demanding and are therefore typically used to study specific issues of a subsystem. The results of such coupled simulations are then abstracted or used to justify a simplified treatment or conservative assumptions made in a system-level model. For these generic analyses, we did not simulate coupled THC or THM or THMC processes but included some of the effects of such processes through effective parameters and conservative assumptions.

21. Q: Have you planned some scenarios analyzing the stress state of the horizontal well environment? (Such as) over-the-well stability and influence of the stresses on the radionuclide migration?

    A: We have not performed a geomechanical analysis. We are aware that such analyses are important to assess seismic risks, optimal borehole orientation, the likelihood of fault reactivation, borehole deformation or convergence, etc. Most of these issues are best addressed by specialized submodels, the results of which are subsequently included in a system-level model. For example, the extent and properties of an excavation-disturbed zone can be analyzed and then indirectly included in the simulations through the use of effective parameters that govern fluid flow and radionuclide transport.

22. Q: Have climate change projections been included in your modeling for the borehole repository such as an increase in temperature/precipitation?

    A: The effects of a changing climate have not been included. For a deep repository in the saturated zone, the impact of climate-induced precipitation changes is considerably weaker than for a mined repository in the unsaturated zone. Notable exceptions are ice ages and the associated advance and retreat of glaciers, which affect pore pressures and effective stresses, as well as groundwater geochemistry to the circulation depth. Finally, changes in temperature and precipitation due to climate change affect the near-surface ecosystem and therefore the pathways by which people may be exposed to radiological effects.

23. Q: If I understand this correctly, the radiological impact is dependent upon demonstrating that due to hydrostatic pressure, water does not boil during the initial thermal period (1,000 years). From a licensing perspective, how does Deep Isolation propose to demonstrate that without human intervention, hydrostatic pressure will be maintained throughout the thermal period?

    A: An approximately hydrostatic pressure profile is the natural state of the system, i.e., pressures at depth tend to be high, increasing by approximately 1 bar per 10 m of depth. Because it is the natural state the system tends to equilibrate to, there is no need for active human intervention. In fact, the opposite is the case: Considerable human intervention is needed in the form of continuous pumping to reduce the pressure at depth, as is the case for a mined repository during the construction and operation phase. While pressures at depth may be lower or higher than hydrostatic, they are considerably higher than near-atmospheric pressures with water boiling at 100ºC. Also, note that boiling — which is very unlikely to occur in a borehole repository — may be a complicating factor but does not necessarily have a significant detrimental effect on dose.

24. Q: What is the post-closure Performance Assessment and criticality of the system and its potential impact to groundwater? Have you considered a criticality event to occur in the deep borehole?

    A: The main goal of the generic safety calculation is to evaluate the performance of the deep horizontal repository system and its impact on radionuclide concentration in groundwater and the resulting exposure dose. The generic repository system is assessed to be safe despite conservative assumptions and the evaluation of a wide range of properties and conditions. Moreover, it is expected that the spent nuclear fuel would remain subcritical in the disposal section. Positive reactivity feedback of the waste is unlikely given the linear, end-to-end arrangement of individual assemblies. No detailed criticality analysis has been performed yet, but a full analysis of potential criticality events will be included in a comprehensive safety analysis.

25. Q: Are you concerned about groundwater flow? I know you're targeting shales with ancient groundwater, but over 1E6 years, groundwater may flow quite a distance.

    A: Groundwater flow (and associated advective transport of radionuclides) is one of the key processes accounted for in our generic safety assessment model. We tried to emphasize that we made conservative assumptions regarding shale permeability and pressure gradients, which tend to increase groundwater flow and advective transport. The resulting concentration plumes clearly show an advective component in the host rock; transport in the overburden (and aquifer) is advection-dominated. We are indeed “concerned” about groundwater flow in the sense that we account for it; we are less concerned about its detrimental impact on the calculated radiation dose to the reasonably maximally exposed individual, as the deep horizontal disposal concept provides sufficient isolation of the waste from the biosphere.

26. Q: What are the results to date on thermal-hydrological modeling of the envisioned disposal concept in low permeability host rock?

    A: The thermal-hydrological modeling show that (1) the calculated radiological exposure dose to an individual living at the repository site is very small, i.e., far below a stringent dose standard, and (2) this result is robust to changes in assumptions and accounting for a wide range of uncertain parameter values. The results of the safety calculations are described in detail in the Safety Calculation Report.

27. Q: How many simulations did you do in the randomized set?

    A: Four hundred realizations were simulated, which is considered sufficient to generate informative histograms of peak dose values.

28. Q: What is your period of performance in years? I believe Yucca Mountain was held to a million years or more.

    A: The Deep Isolation model evaluated repository performance up to 10 million years, which is long enough to capture the peak radiological exposure dose for a wide range of properties, assumptions, and scenarios. The Yucca Mountain performance period was 1 million years.

29. Q: What are the uncertainties involved in the Safety Calculations?

    A: A probabilistic analysis has been performed to examine the impact of parametric uncertainty and spatial variability on the calculated peak dose. For these generic safety calculations, random parameter values were sampled from very broad uncertainty distributions (for example, permeabilities of the shale host rock were sampled over a range of four orders of magnitude). The Monte Carlo analysis included uncertainties not only in material properties, but also the radionuclide inventory, waste degradation rates, initial and boundary conditions, structure of the heterogeneity and other assumptions that could be parameterized. The impacts of spatial variability were also included. In addition to this probabilistic analysis, we conducted various sensitivity analyses to examine the impact of discrete changes in influential assumptions and parameters on the calculated system behavior. The explored range is wide, reflecting that no site-specific characterization data can be used in a generic analysis. These sensitivity and uncertainty analyses indicate that the conclusions drawn from the calculated exposure dose remain valid even if considerable changes are made in key assumptions, uncertain parameters and unidentifiable spatial variability.

The probabilistic analysis is discussed in Section 4.7.4 of the Safety Calculation Report, with chosen uncertainty distributions given in Appendix B.

30. Q: Especially for research reactors, spent fuel with aluminum alloy gas generation can be large. Any risk of forming a free gas phase and subsequent hydrofracturing?

    A: These generic safety calculations were concerned with the disposal of spent nuclear fuel assemblies from commercial pressurized water reactors. While many other waste forms, including those from research reactors, are potentially suitable for disposal in a horizontal borehole repository, waste-specific features and processes, including gas generation, would need to be examined in a safety analysis that is targeted to these particular waste forms.

31. Q: More discussion (is needed) on spent fuel burn-up rates and gas composition; scaling up from 50 m one borehole with 150 canisters to a full scale 1 km wide repository with 1,500 canisters; colloidal transport of sorbing radionuclides like Tc-99.

    A: For the current analysis, we selected characteristics of commercial spent fuel with an initial enrichment of 4.73 percent, a burn-up of 60 GWd/MTIHM and a cooling time of 30 years.

    The calculations are based on parallel boreholes 100 m apart from each other (50 m is the distance from the borehole axis to the symmetry plane between two boreholes). For the chosen configuration (specifically with multiple drinking water wells at the land surface), the shape and concentrations of the contaminant plumes and the exposure dose calculated for a repository with 10 boreholes are the same as those for 1 borehole (due to symmetry); the dose is approximately inversely proportional to the spacing between boreholes.

    For colloidal transport to occur, the pores in rock formations must be large (to avoid straining and filtration), and there must be significant groundwater flow and advective transport. Both conditions may be prevalent in unconsolidated alluvial deposits or in fractured rocks. In tight, low-porosity host rocks, filtration is very strong, essentially immobilizing radionuclide-bearing colloids. In the case of reversible radionuclide sorption on colloids and a preferred affinity of radionuclides for the accessible rock surfaces, colloidal radionuclide transport is not important. Colloidal transport of Tc-99 may be relevant in fractured rocks or along an open casing annulus; however, it is not considered in the current safety calculations of a shale repository.

32. Q: With the probabilistic calculations, could you have greater connectivity if correlation between parameters was accounted for?

    A: Spatial correlations in the property field are accounted for, leading to the inclusion of larger-scale “connectivity.” We understand that uncertain parameters may be statistically correlated to each other. For example, a rock with lower porosity tends to have lower permeability and lower effective diffusivity (assuming this is meant by “connectivity” in this question). If sufficient cross-data between the potentially correlated parameters are available, a covariance can be determined and accounted for during Monte Carlo sampling. In this generic Safety Calculation Report, the random samples are considered independent of each other. Note, however, that the Latin Hypercube Sampling algorithm implemented in the iTOUGH2 simulation-optimization framework has the capability to account for correlations among uncertain input parameters, a feature that may be used in subsequent safety analyses should defensible information about the covariances become available. The impact of correlations can also be examined in a sensitivity analysis.

33. Q: If you have done a sensitivity analysis, what was the most influential parameter affecting peak dose?

    A: Identifying and ranking the influence of input parameters is challenging because (1) the dimension of the parameter space is very large; (2) parameter ranges and standard deviations are wide for a generic analysis; (3) the calculated response is non-linear to changes in the input parameters; and (4) the ranking is necessarily based on some subjective scaling factors. For this situation, a so-called “global” (rather than “local”) sensitivity analysis is needed, requiring a very large number of simulations — specifically if sampling-based Sobol’ coefficients are to be determined. Such a formal, comprehensive analysis is not warranted at this stage. Note, however, that we conducted standard (local) sensitivity analyses to examine the influence of permeability, diffusivity, pressure gradient, waste degradation rate, repository depth, the presence of a fault and early waste canister failure on exposure dose. While these sensitivity analyses provide valuable insights into the system behavior, it might be misleading to call out a single (or a few) parameters as the “most influential” factors, for the reasons given above.

34. Q: Could you go into more detail on how you modeled the excavation disturbed zone (EDZ) in both the Vertical and Horizontal section?

    A: The EDZ is modeled as a ring-shaped zone around the entire length of the borehole with an axial permeability that is (conservatively) two orders of magnitude higher than the formation it goes through. The thickness of the EDZ is half the radius of the borehole, which changes along the trajectory of the borehole. The EDZ is conservatively assumed to exist throughout the simulation period, i.e., we do not account for self-healing or plugging, as may occur in a shale formation.

Canister Questions

35. Q: For the generic disposal design, how many fuel assemblies per canister, and how many canisters fit into the waste disposal section of one borehole?

    A: Each canister contains a single spent fuel assembly from a Pressurized Water Reactor (PWR). A 1 km-long disposal section holds about 150 canisters. An array of 10 parallel disposal sections holding a total of 1,500 PWR assemblies would accommodate the waste being produced by a 1,000 MWe nuclear power plant in 30 years.

36. Q: Can you discuss your assumptions regarding canister integrity over time?

    A: Payer et al. (*Energies*, *12*(8), 1491, 2019; Corrosion Performance of Engineered Barrier System in Deep Horizontal Drillholes) estimated the Deep Isolation canister will remain intact for at least 50,000 years under typical repository conditions (reducing environment, enhanced temperatures and salinity). However, the safety calculations are based on a more cautious assumption: In the reference scenario, all canisters are assumed to be breached after 10,000 years, giving full access to water entry as well as the release of dissolved radionuclides. We also considered an early-canister-failure scenario (see Section 4.3.3.3 of the Safety Calculation Report) and an instant-waste-mobilization scenario (see Section 4.7.3.1 of the Safety Calculation Report). Both scenarios assume that all canisters fail immediately after repository closure.

37. Q: What was the assumed diameter of your borehole, and is it feasible using current technology?

    A: The modeled diameter of the horizontal waste disposal section of the borehole is 19 inches (48.26 cm). The diameters of the conductor hole at the surface, the vertical access hole and the curved section are somewhat larger. For details on borehole and casing diameters, please see Table 5 in Appendix C of the Safety Calculation Report. Horizontal boreholes of such diameters can be drilled in shale using current technology.

38. Q: What are the maximum diameter and length of a disposal canister compatible with the horizontal borehole?

    A: We have not specifically identified the maximum diameter of the disposal canister. The length of a disposal canister should not be a limiting factor as drilling companies typically handle pipes that are 90 feet (27 m). A canister holding a PWR fuel assembly has an outer diameter of approximately 13 inches (33 cm) and a length of about 18 feet (5.5 m), which includes end caps and a latching mechanism for emplacement and potential retrieval of the canister. Most other waste forms (e.g., fuel assemblies from Boiling Water Reactors, cesium (Cs) and strontium (Sr) capsules, etc.) would fit into smaller canisters and more narrow boreholes. Larger waste forms, such as vitrified high-level waste canisters, may require a larger borehole up to 24 inches (60 cm). Larger waste forms would benefit from additional research and review.

39. Q: How do graphs change if corrosion occurs well before the 100,000-year mark?

    A: In the Deep Isolation generic safety calculations for shale, the canisters are modeled to fail at 10,000 years, well before the 100,000-year mark. Canister durability is expected to be much longer, but in our safety calculations, we make the conservative assumption that canisters fail early. We also considered an early-canister-failure scenario (see

Section 4.3.3.3 of the Safety Calculation Report) and an instant-waste-mobilization scenario (see Section 4.7.3.1 of the Safety Calculation Report). Both scenarios assume that all canisters fail immediately after repository closure. Early canister failure leads to only a modest increase in the peak dose. This is due to the great depth, relatively slow degradation of the ceramic uranium dioxide waste, and inherent passive protection provided by the geology.

40. Q: In your calculations of radionuclide dispersion, what is the time of the first release of waste from the canister? I ask because I estimate that the general corrosion rate of Alloy 22 is less than 0.01 microns per year, suggesting that the time of first release will be more than 10,000 years. Do you intend to take that into account?

    A: In the Deep Isolation generic safety calculations for shale, the time of first release is 10,000 years. This is a conservative assumption and tests the robustness of the geologic environment as a natural passive barrier.

41. Q: I would like to know what properties of canister and casing in considerations of high temperature, ground pressure and water condition.

    A: The generic safety calculations do not directly simulate the chemical and mechanical processes affecting the integrity or lifetime of the canister and casing. Instead, we make conservative assumptions on casing and canister lifetimes based on estimated corrosion rates. These assumed canister and casing lifetimes are considerably shorter than corresponding estimates documented in a peer-reviewed Deep Isolation paper (Payer et al., *Energies*, *12*(8), 1491, 2019; Corrosion Performance of Engineered Barrier System in Deep Horizontal Drillholes). In the model base-case scenario, the casing failure occurs at 100 years, and canister failure occurs at 10,000 years. Corrosion of the initially impermeable canister and the casing is accounted for in the numerical model by increasing their permeabilities to high values at these times, effectively releasing the radionuclides into the geosphere without restriction. In the early failure scenario, the canisters and casing fail instantly, i.e., just after the repository is sealed. We explored this scenario to understand the relative importance of canister and casing corrosion on repository safety. We found that there was little difference in the peak dose between the base-case scenario (canister fails at 10,000 years) and the early failure scenario (canister fails in year one). Hydrological and thermal properties defined for the canister and casing are provided in the Safety Calculation Report documentation (see Appendix B of the Safety Calculation Report).

42. Q: What was the fractional degradation rate you used and where did you get that rate? Was this based on the dissolution coefficient of uranium oxide?

    A: We used a conservatively high fractional waste degradation rate of 10^{-5} per year based on values used by Sandia National Laboratories. Studies performed by SKB and others suggest that the rate is more likely on the order of 10^{-7} per year or lower, depending on the geochemical environment; this case is considered in a sensitivity analysis (see Section 4.7.3.1 of the Safety Calculation Report). Note that we also performed a very conservative bounding calculation assuming instant waste degradation, referred to as the “instant radionuclide mobilization scenario.”

Radionuclide Transport

43. Q: Have you considered the long-lived, alpha-emitting actinides?

    A: Long-lived alpha-emitting actinides (metallic elements with atomic numbers between 89 and 103) are present in canisters but are not mobile enough in the reducing environment to warrant inclusion in this generic model (see discussion about the selection criteria of safety-relevant radionuclides). The set of potentially safety-relevant radionuclides will be re-evaluated and expanded once site-specific characterization data become available and a comprehensive safety assessment is performed.

44. Q: Why are other radionuclides not really that important in deep subsurface?

    A: Nuclear waste is comprised of more than 100 different radionuclides. If accidentally released at the land surface shortly after removal from the reactor, their total activity (which is related to the isotope's abundance and decay constant) and toxicity are a measure of their relative danger to exposed people. The ultimate purpose of waste disposal in a deep geologic repository is to make sure that the danger the waste poses to future generations is decoupled from the danger it presents if it were released today at the land surface. This goal is accomplished by removing the waste both in space and time from people and the environment. By doing so, many of the most dangerous radionuclides decay, either while still encapsulated in the solid waste matrix, or on their very long migration from the repository to the accessible environment. As a result, only a small fraction of the radionuclides present in the initial inventory contribute significantly to the total dose.
    Moreover, criteria other than activity and toxicity become dominant when compiling the list of radionuclides that are relevant for long-term safety. Therefore, this list is different from and much shorter than the list of radionuclides that are of concern at the time of disposal. All radionuclides present in canisters are considered, but most are not mobile or long-lived enough in the geological environment to warrant inclusion in a generic model used for assessing long-term safety. For these generic calculations, ^{129}I, ^{36}Cl, ^{79}Se, and ^{99}Tc are selected for numerical evalua-tion. ^{129}I is the main isotope of concern because it is long-lived, abundant in the original waste, relatively toxic and very mobile in aqueous environments under reducing conditions. This list of safety-relevant radionuclides is consistent with the radionuclides emerging in other, comprehensive safety analyses for repositories in argillaceous formations under reducing conditions (Andra, 2005; Nagra, 2012; NWMO, 2013) as the main contributors to the annual individual effective dose.

45. Q: Can you comment on the effect of corrosion and gas generation on radionuclide migration in the near field.

    A: Gas generation from waste degradation and canister corrosion has not been explicitly accounted for in the current generic safety calculations. The decision to not include gas generation was based on a separate analysis (using conservatively high corrosion rates) that show that: (A) given the waste density and geometry of the borehole repository, the hydrogen generation rate per volume is relatively low; (B) due to the high *in situ* pressure, most of the generated hydrogen is dissolved in the brine; (C) the dissolved hydrogen diffuses away radially, which rapidly reduces its concentration to values farther below the bubbling point; (D) while a free gas phase does indeed evolve immediately around the canister and casing, the volumetric gas saturation is very small due to the high pressure, and this small volume does not lead to significant advective flow (potentially displacing contaminated water); (E) the pressure buildup in the EBS is small for the given (relatively high) shale permeability, far below the threshold values for pathway dilation and/or hydraulic fracturing; and (F) the free gas phase disappears relatively quickly due to redissolution of the hydrogen in the brine.

We acknowledge that corrosion and gas generation mechanisms and their impact on the engineered barrier system and near field need to be assessed once site- and design-specific conditions and properties are available. Based on our current understanding, however, it is not expected that these phenomena, which occur shortly after repository closure, detrimentally affect the long-term safety of the horizontal borehole repository.

46. Q: How do you keep the radioactive material from leaking into the aquifer?

    A: Understanding regional hydrogeology is a fundamental aspect of our site selection and repository design. Our repositories are sited thousands of feet below near-surface aquifers in low permeability rock formations such as shale. The initial protection provided by disposal canisters (>10,000 years) and the relative insolubility of the spent uranium dioxide (>300,000 years for dissolution) retard the release of radionuclides into the geosphere. When radionuclides do enter the geosphere, some radionuclides either sorb to the mineral surfaces, or react chemically and form insoluble phases. The long-lived and mobile radionuclides such as iodine-129 and chlorine-36 diffuse slowly through the rock volume and arrive at the surface aquifer in very low concentrations after a very long time. In our Safety Calculation Report, the peak dose in the aquifer occurs after 1.6 million years and is very low, ~1,000 times lower than the stringent 10 mrem/year safety standard we have adopted.

47. Q: How did you model the amount of radionuclides that would be captured by the near-surface aquifer?

    A: Fluid flow and radionuclide transport from the repository through the deep subsurface into and within the aquifer are simulated using a physics-based flow and transport model. In particular, the zone of influence of the drinking water well (and thus its ability to capture the radionuclides that enter the aquifer) is the result of such a simulation (i.e., not a predefined, external assumption). For the chosen setup with a regional upward pressure gradient, essentially all radionuclides released from the waste canisters would eventually end up in the drinking water well or decay on their long journey through the geosphere to the aquifer. Thus, the very low dose rate from the drinking water well shows the safety of the deep horizontal borehole repository concept.

Disruptive Events

48. Q: You mentioned earthquakes, but storing nuclear waste requires such a lengthy time frame that plate tectonics need to be factored in. Did you include the inevitability of plate movement over these long time frames in your model? I'm including decay chains in this time frame, as should you.

A: In the current analysis, plate tectonic is not explicitly simulated, as siting a repository in close proximity to tectonic plate boundaries is a special scenario that is unlikely or can be avoided. The impact of fault activation by earthquakes (which may be triggered by tectonic events) has been included.
Decay chain products can and certainly will be considered if relevant. The dominant radionuclide is I-129; its daughter product is Xe-129, which is stable, i.e., has no radiological effects and thus does not need to be tracked. In a comprehensive, site-specific safety analysis, we will include decay chains (e.g., the uranium series). Also, very short-lived daughter products are typically directly included in the dose coefficient.

49. Q: Does your disruptive event modeling include an assumption that your disposal hole would have retained its structural integrity prior to, in this case, the earthquake? And, what are the radial impacts of the pressure caused by multiple drillings in the horizontal disposal field?

    A: The modeling of the seismic event scenario considers the borehole to be structurally intact prior to the earthquake, with waste degradation and radionuclide releases described by the processes included in the reference scenario. Note that early-waste-failure and instant-waste-mobilization scenarios were also evaluated.

    Pressure perturbations during drilling and waste emplacement are very small and do not propagate very far in a radial direction given the low permeability of the host rock. After repository closure and after the dissipation of thermal expansion effects, the borehole is in near equilibrium with the surrounding pressure field. Therefore, we do not anticipate detrimental pressure or effective stress interferences between parallel boreholes.

50. Q: How do you manage seismic events?

    A: Seismic events are managed starting with site selection and are considered throughout the entire design of a Deep Isolation repository. We attempt to mitigate the consequences of seismic events by locating the waste at a great depth in a low permeability hydrological environment. The disruptive scenario is one example of the modeling efforts that Deep Isolation has taken to further understand the risks of a very large (and very low probability) fault rupture event.

51. Q: Performance Assessment results clearly show an insignificant passive impact. But what about the inadvertent human intrusion, such as drilling for mineral resources. Have human intrusion scenarios been analyzed?

    A: Inadvertent human intrusion scenarios have not yet been analyzed but will be included in a comprehensive safety analysis. The considerable depth of the repository reduces the economic value of a potential resource and — combined with the small repository footprint — reduces the probability of a direct hit of the horizontal borehole by an exploration borehole and reduces the consequences of such an intrusion.

52. Q: Have you looked at the case where hydraulic fracturing occurs in the distant future?

    A: This scenario has been previously brought to our attention as a variant of the inadvertent human intrusion scenario. The issue can be partially mitigated by defining the presence or absence of recoverable and economically viable natural resources as a siting criterion, or by specifying appropriate requirements for the host rock (e.g., requiring a minimum clay content or ductility parameter for the shale, making hydrofracturing ineffective and the host rock unsuitable for resource extraction by hydraulic fracturing).

53. Q: Did you consider the permeability of the grout/concrete used to seal the borehole and any disruptive events that may reduce the permeability of the grout over time?

    A: We did not make assumptions about the temporal changes (whether increases or reductions in permeability) of the buffer, sealing and backfill materials. Relatively high, conservative values were selected (Appendix B of the Safety Calculation Report contains a complete list of the permeabilities of all natural and engineered materials represented in the model). Uncertainties in the permeability of backfill and sealing materials have been included in the probabilistic safety analysis.

54. Q: Have you considered a scenario in which the cement/grout seals of the engineered barrier system are not effective and there is groundwater communication? And did you consider a backfill failure scenario for the drill hole and the borehole?

    A: We assumed relatively high permeabilities of all backfill materials, with higher permeabilities evaluated during the probabilistic safety analysis. Moreover, backfill failure scenarios-combined with fault reactivation scenarios-have been analyzed and will be documented in the future. Despite the existence of a connection along the borehole between the disposal section and the aquifer, radionuclide releases through this narrow pathway are very small, and the impact on peak dose is insignificant.

55. Q: Do we assume that in the event of a fault through the borehole, that the fault stays open?

    A: The permeability of the fault and the surrounding fracture zone remains high throughout the simulated time. This is a conservative assumption. Typically, faults close up with time (and may even become sealing faults), specifically in shale formations.

56. Q: We don’t see any movement upward toward the vertical section of the borehole as we do with the disruptive fault scenario. Could you explain why there is no travel up the disturbed zone and/or vertical section?

    A: There actually is some upflow along the access hole and the associated excavation disturbed zone (EDZ). However, this axial flow and radionuclide transport are very small (see Figure 10 of the Safety Calculation Report) leading to insignificant releases to the biosphere. The rates are small mainly because of the inherent design features of the repository system, as discussed in Section 5.2 of the Safety Calculation Report.

Legislative and Regulatory Matters

57. Q: Have you had any interactions with the NRC about your analysis?

    A: We have not yet shared our Safety Calculation Report with the NRC, but we are preparing to do so as we develop this work toward a comprehensive safety case.