# Deep Isolation Response to Krall, McCartin, Macfarlane, "Siting Deep Boreholes for Disposal of Radioactive Waste: Consequences for Tight Coupling between Natural and Engineered Systems", January 2020

## Response Summary

In January 2020, Lindsay Krall, Timothy McCartin, and Allison Macfarlane (KMM) published a critical review of vertical and horizontal borehole disposal of nuclear waste. They explicitly name *Deep Isolation* as a proponent of the horizontal approach. In their article KMM present a compendium of groundwater and geological issues that must be addressed for any geologic waste disposal and siting approach. The overall thrust of the article is to discredit the capacity of geologic formations to reliably retain radionuclides and to function as a primary safety barrier. In the *Deep Isolation* approach the geosphere is indeed believed to contribute considerably to repository safety, reducing the requirements that need to be imposed on the performance of the engineered barrier system, whose long-term performance is difficult to assess. This is consistent with the assumptions made in other published safety analyses for mined repositories located in or below argillaceous formations, where the depth of burial and the functional properties of the geosphere are considered primary barriers. *Deep Isolation* does not make assumptions that the conditions identified by KMM are absent from their prospective sites. Rather, *Deep Isolation* is acutely aware of the wide range of properties encountered in the subsurface and works to create a solution that adheres to design objectives of safety in depth. *Deep Isolation* welcomes this discussion and scrutiny from people committed to the waste disposal challenge and we hope our responses are viewed likewise. *Deep Isolation* is confident in its approach and rejects the notion that a generic list of potentially safety-relevant factors render the deep horizontal drillhole concept in any way less viable than a mined repository.

## Background and Introduction

Lindsay Krall, Timothy McCartin, and Allison Macfarlane published a Critical Review entitled "*Siting Deep Boreholes for Disposal of Radioactive Waste: Consequences for Tight Coupling between Natural and Engineered Systems*" in *Environmental Science & Technology* (Krall et al., 2020, doi: 10.1021/acs.est.9b03440). The stated intent of this review paper is to "summarize some geologic considerations … that challenge the long-term safety case for deep borehole disposal of SNF".

KMM address two borehole concepts: vertical and horizontal. They explicitly name *Deep Isolation Inc.* as a proponent of the horizontal approach. The two methods, vertical and horizontal, despite the fact that they both involve drilling narrow holes deep into bedrock, have important and fundamental differences in their technologies and approaches to safety. In this response we focus on the horizontal drillhole method, since that is the one we have analyzed in depth. (To help distinguish the two approaches, we will use the term "borehole" for the vertical repository, and "drillhole" for the horizontal one, and "borehole" when discussing both together.)

KMM present a useful compendium of issues that must be addressed in choosing any geologic waste disposal method and site. As quoted above, they do indeed challenge the horizontal

drillhole approach. However, their analysis is largely based on inappropriate and misapplied assertions and lacks crucial information regarding our analysis of the borehole concept. We submit to understanding this, since the concept is new, and not all of the work done by *Deep Isolation* is yet public.[1] We would, however, prefer to be engaged by those who are closely examining and questioning our work so that we may share as much information as possible. A core philosophy of *Deep Isolation* is that it will take the combined thinking and scrutiny from a body of committed people to tackle the challenge we are taking on. It is in this spirit that we received the paper, and we hope our responses will be viewed likewise.

In this reply we respond to the substantive issues raised by KMM. Of course, the questions asked by KMM will additionally and necessarily be addressed in detail in a future license application. We are confident that we will be able to demonstrate the safety of disposing nuclear waste in a deep drillhole repository.

Our discussion starts with a summary of the central assertions made by KMM, followed by more detailed comments.

## Summary of Assertions

The review paper provides a historical overview of various borehole disposal concepts and proceeds to list issues—mainly geological and hydrogeochemical, but also operational—that the authors consider problematic, i.e., challenging the safety as well as engineering and economic viability of the borehole disposal concepts. The paper can be summarized as consisting of the following assertions:

(1) Water-conducting faults and fractures exist everywhere in the geosphere; they promote fluid flow and thus advective radionuclide transport.
(2) Groundwater dating is difficult and results may be misleading; therefore, the stationarity of deep groundwater cannot be proven.
(3) Because of (1) and (2), safety cannot be based on the natural barrier system alone—one must rely on the engineered barrier system.
(4) Due to size limitations in a borehole, the engineered barriers are weaker than those that can be constructed in a mined repository.
(5) The engineered barriers in boreholes degrade faster due to the harsh geochemical conditions encountered at depth.
(6) The properties of the host rock and the integrity of the canisters after emplacement can only be assessed by direct visual inspection by humans underground.
(7) The geographical extent of formations with suitable conditions is narrow, questioning the advantages of modularity and cost-effectiveness of the drillhole concept.
(8) Detailed numerical modeling based on site-specific information is needed.

[1] Note that *Deep Isolation* has published three peer-reviewed articles in the open-access journal *Energies*, well before KMM submitted their review article (Finsterle et al., *Energies*, *12*(4), 596, https://www.mdpi.com/1996-1073/12/4/596/pdf; Payer et al., *Energies, 12*(8), 1491, https://www.mdpi.com/1996-1073/12/8/1491/pdf; and Muller et al., *Energies*, *12*(11), 2052, https://www.mdpi.com/1996-1073/12/11/2052/pdf); only one of these three articles is cited in KMM.

(9) Because of the above assertions, the safety case for a borehole disposal concept is considered inferior to that of a mined repository.

## General Reply to Assertions

The assertions made by KMM are accompanied by numerous references from the hydrogeological and geochemical literature. These references are used to support individual property values and associated statements, most suggesting that they adversely affect repository performance, thus calling the viability of the drillhole repository concept into question.

*Deep Isolation* appreciates and values the compilation of such a list of potentially detrimental factors and agrees that they need to be characterized and properly represented in a site-specific safety case. However, we believe that a mere delineation of individual features does not lend itself to conducting an objective evaluation of the drillhole repository concept. Understanding the safety of the overall repository system not only depends on comprehending the effectiveness and reliability of each barrier component, but needs to account for each component's respective role within an integrated safety concept. The review paper makes conclusions about the safety case of a drillhole repository without an integrated analysis or discussion of the details of the design or a self-consistent description of site-specific conditions, and without attempting to address how the site and the engineered systems work together.

Furthermore, the data used to support assertions appear somewhat selective and disconnected from each other. The presentation of a list of potential issues seems to indicate that the repository safety elements act like links in a chain rather than being multiply redundant, giving the impression that the presence of any unfavorable condition significantly undermines the safety case and thus the entire concept. Finally, many of the issues raised by the authors also apply to mined repositories which, in addition, have their own specific shortcomings; these are not mentioned in their review, even though some of the conclusions suggest that a comparative analysis was performed.

## Summary Replies to Specific Assertions

The following provides some general comments related to each of the assertions mentioned above.

(1) *Fractures and advective transport*

The prevalence of fractures is acknowledged. However, fractures do not necessarily disqualify a host rock in the absence of substantial upward driving forces or an understanding of the capacity of a given fracture to support quantitatively important upward transport. Moreover, many of the references (e.g., in KMM Table 2) refer to geothermal sites (which are naturally located in critically stressed upflow regions) and the scenario of KMM Figure 4 is for an artesian system, where the horizontal drillhole was placed above the aquifer. No such regions or configurations would be considered for a deep horizontal drillhole repository, and their inclusion in the KMM analysis is irrelevant to the Deep Isolation approach. Data from exploration holes drilled for the characterization of potential host rocks for a nuclear waste repository would be more relevant, but are not discussed.

(2) *Groundwater dating*

The challenges of sampling at depth are recognized. However, considerable advances have been made in collecting and analyzing uncontaminated samples for many independent isotopic systems. The information from such samples and other complementary data sets can be used in an integrated analysis to determine age, mixing, and regional flow direction of groundwater.

(3) *Reliance on the natural barrier system*

The geosphere is indeed believed to contribute considerably to repository safety, reducing the requirements that need to be imposed on the performance of the engineered barrier system, whose long-term performance is difficult to assess. This is consistent with the assumptions made in other safety analyses for mined repositories located in or below argillaceous formations, where the depth of burial and the functional properties of the geosphere are considered primary barriers.

(4) *Weak engineered barriers*

The key component of the engineered barrier system is the waste form, which is the same for the drillhole and mined repository concepts. The relevance of secondary components (such as canister and buffer) on overall performance of a deep horizontal drillhole repository has been assessed and is considered minor if the site has been properly selected. The relative simplicity of the secondary engineered barrier components in a drillhole repository increases the robustness of the system and of our understanding of it.

(5) *Harsh geochemical conditions*

Geochemical conditions and their impact on degradation and transport processes must be accounted for—at any site and for any disposal concept. For a horizontal drillhole repository at relatively shallow depth, the conditions are similar to those experienced by a mined repository; for comparatively deeper repositories, the impact of harsh geochemical conditions on waste degradation and near-field transport is less relevant for total system performance.

(6) *Verification of geology and waste emplacement by humans underground*

The requirements for supporting the presence of humans underground in large ventilated caverns for multiple decades considerably disturbs the host rock and near-field conditions in mined repositories. These perturbations increase the demands on characterization data and their interpretation. The additional information to be obtained from direct visual inspection by humans underground is limited. Much of the primary geologic and hydrologic data required for site characterization in mined repositories relies on the same types of drillcore data, remote geophysical sensing, and large-scale geological mapping that will be used to assess horizontal drillhole repositories. The remotely controlled emplacement of heavy canisters and installation of large buffers in a mined repository also pose a risk for damage to the canisters, which cannot be visually inspected after buffer installation.

(7) *Small geographical extent of suitable sites*

The suitability of potential host formations must be assessed by regional and local site characterization; the geographical extent of suitable sites cannot be determined from continental-scale maps, and their use for this purpose is ill-advised.

(8) *Site-specific data and modeling*

We fully agree that the safety of a horizontal drillhole repository must be assessed in a safety analysis that is solidly based on advanced modeling and site-specific data. The KMM review is based on generic data. Moreover, the modeling used by *Deep Isolation* for

the assessment of a drillhole repository is far more sophisticated than what is implied in Section 4 of KMM.

(9) *Safety case*

The review article draws conclusions about the safety and thus viability of a deep horizontal drillhole repository without having performed, discussed, or reviewed a comprehensive safety analysis, which is needed to evaluate the relevance of each of the potentially detrimental factors listed in the article for repository performance. Moreover, mined repositories cannot be declared superior to horizontal drillhole repositories without a comparative analysis of their respective repository performance.

## Overall Assessment of the KMM Review Article

The review by KMM is a welcomed contribution to the discussion of borehole disposal as a viable alternative to the standard concept of mined repositories. The article summarizes features and conditions that need to be properly evaluated when assessing a nuclear waste repository—be it drilled or mined.

However, the review article makes general statements about the safety case of a horizontal drillhole repository without performing an integrated analysis—generic or site-specific—which would reveal the actual relevance of each of the listed features and conditions and how they work together for the ultimate purpose of protecting humans and the environment from radiation.

*Deep Isolation* does not make explicit or implied assumptions that the detrimental features or conditions identified by KMM are absent from their prospective sites. By contrast, *Deep Isolation* is acutely aware of the wide range of properties and conditions encountered in the subsurface. *Deep Isolation* therefore follows a process in which site selection is based on a set of criteria and requirements. Our site characterization and performance assessment efforts, through which assumptions are evaluated and replaced with site-specific evidence, aim at informing regulators and the public on whether a potential site meets these requirements before it considers a site viable as a host for a deep drillhole repository.

However, *Deep Isolation* rejects the notion that a generic list of potentially safety-relevant factors renders the deep horizontal drillhole concept inherently unsafe or unfeasible, or makes it less viable than a mined repository.