APAC Safety Calculation Webinar Q&A

Q1: Uncertainties involved in the calculation?

A1: We presume this question is concerned with a more detailed description of the framework for the probabilistic analysis and resulting uncertainties in the calculation of peak dose characteristics for the generic safety case.

A probabilistic analysis has been performed to examine the impact of parametric uncertainty and spatial variability on the calculated peak dose (and the time peak dose is reached). For this 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 technical report, with chosen uncertainty distributions given in Appendix B.

Q2: I'm aware of the deep vertical borehole concept. Can you describe the pros and cons of horizontal boreholes in comparison with vertical?

A2: We would like to defer the answer to this question. Doing a comparative analysis would require a considerable effort to make sure the two concepts are compared "on equal footing." Some of the issues that concern the vertical borehole design become less important for horizontal disposal; these differences between the two concepts were mentioned during the Q&A session of the Webinar (see response A14) and are discussed in Muller et al. (2019; *Energies*, *12*(11), 2052; https://www.mdpi.com/1996-1073/12/11/2052/pdf). We consider the deep vertical borehole concept (and mined repositories) viable alternatives to our deep horizontal drillhole concept.

Q3: 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.

A3: 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 and that transport in the overburden (and aquifer) are even 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.

Q4: Can you comment on the effect of corrosion and gas generation on radionuclide migration in the near field.

A4: 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 drillhole 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; this small volume does not lead to significant advective flow (potentially displacing contaminated groundwater); (e) the pressure buildup in the EBS is small for the given (relatively high) shale permeability of 1E-17 m2, far below the threshold values for pathway dilation and/or fracking; 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 EBS 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 drillhole repository.

Q5: 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?

A5: There is considerable flexibility in the potential layout of the repository (parallel, radial, sectoral, vertically staggered, from central drill pad or multiple drill pads, following stratigraphic units, accounting for orientation of stress field, etc. 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; cost), but may also have disadvantages (e.g., waste emplacement and retrieval operations; inability to align with orientation of stress field; cost). The repository layout will be optimized for the conditions encountered at a specific site. (See also response A18.)

Q6: 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?

A6: 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 drillhole repository, waste-specific features and processes (including gas generation) would need to be examined in a safety analysis that is targeted to this particular waste form. (Please also see A4 for a generic response to the gas generation issue.)

Q7: Can you please motivate some of your assumptions: for instance, why 1km and not 500m or 2km deep? Why is the repository in the transition zone of salinity and not in the saline zone?

A7: While a generic safety calculation may examine a wide variety of assumptions and parameter values, we felt it 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 be non-conservative. 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 technical 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.

Q8: I would like to know what properties of canister and casing in considerations of high temperature, ground pressure and water condition.

A8: These generic safety calculations do not directly simulate the chemical and mechanical processes affecting the integrity or life time of the canister and casing. Instead, we make conservative assumptions on casing (L80 or9Cr-L80 steel) and canister (Ni-Cr alloys, SS alloys) life times based on estimated corrosion rates. These assumed canister and casing life times are considerably shorter than corresponding estimates documented in a peer-reviewed Deep Isolation paper (Payer et al., *Energies*, *12*(8), 1491, 2019; https://www.mdpi.com/1996-1073/12/8/1491/pdf). In the model base scenario, the casing failure occurs at 100 years and canister failure occurs at 10,000 years. Corrosion of the (initially impermeable) canister and casing is accounted for in the numerical model by increasing their permeabilities to high values at these times, effectively releasing all the radionuclides into the geosphere. In the early failure scenario, the canisters and casing fail instantly, i.e., just after the repository is sealed. We explored this scenario in order to understand the relative importance of canister and casing corrosion on repository safety. We found that there was little difference in the peak dose at the surface between the base scenario (canister fails at 10,000 years) and the early failure scenario (canister fails in year 1), i.e., the casing and canister play a minor role in the overall safety of the repository. Hydrological and thermal properties defined for the canister and casing are provided in the safety calculations documentation (see Appendix B of the technical report).

Q9: With the probabilistic calculations, could you have greater connectivity if correlation between parameters was accounted for.

A9: 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 (not sure whether this is meant by “connectivity”). If sufficient cross-data between the potentially correlated parameters are available, a covariance can be determined and accounted for during Monte Carlo sampling. Nevertheless, almost all probabilistic safety analyses assume that the parameters are uncorrelated. In this generic safety analysis, the random samples are also 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.

Q10: If you have done a sensitivity analysis, what was the most influential parameter affecting peak dose?

A10: Identifying and ranking the influence of input parameters are challenging, because (a) the dimension of the parameter space (38) is very large, (b) parameter ranges and standard deviations are wide for a generic analysis, (c) the calculated response is non-linear to changes in the input parameters, and (d) 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 (and may not be feasible). Note, however, that we conducted standard (local) sensitivity analyses to examine the influence on dose of permeability, diffusivity, pressure gradient, waste degradation rate, repository depth, the presence of a fault, and early waste canister failure. While these sensitivity analyses provide valuable insight 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.

Q11: What is the hydrogeological data you need for an assessment of a site, and how can you obtain these? Kf values for a shale are not easy to determine with just one or two orders of magnitude accuracy.

A11: Site characterization needs for a deep horizontal drillhole repository are similar to those of any other disposal concept (with notable exceptions). We can rely on well-established characterization methods used in other nuclear waste isolation programs, but also 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. 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).

Q12: What type of permeability did you use for the shale in the repository section?

A12: The permeability of the shale is indeed one of the most important factors. Shale tends to have a layered structure. We, therefore, assume different, anisotropic permeabilities in horizontal and vertical direction. The horizontal permeability is 1E-17 m2 (which corresponds to 10 microdarcys, or a saturated hydraulic conductivity of 1E-10 m/s); the vertical permeability is an order of magnitude lower. In the probabilistic analysis, we sample 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 that used in other nuclear waste programs that look at clay formations as host rocks. For example, the Opalinus clay in Switzerland has a permeability that is lower than our reference permeability by a factor of at least 1000; the Boom clay in Belgium is 100 times tighter, the reference permeability Sandia used for their analyses of shale disposal in the US is also based on a value 100 times lower; even their excavation-damaged zone is tighter than what we cautiously assumed for our undisturbed host rock!

In short, we did not assume that we have the perfect host rock - we want to develop a repository that is more than adequately safe, and it appears the depth and design of a horizontal drillhole repository can provide that safety even for shale formations that are relatively permeable.

Q13: Do we assume that in the event of a fault through the borehole, that the fault stays open?
A13: The fault is conceptualized as a planar, 50 m wide fracture zone with a high permeability at its center - representing the fault - surrounded by a zone of declining permeability - representing the fracture network created by the fault. The permeability of both the fault and the 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.

Q14: We don't see any movement upward toward the vertical section of the drillhole as we do with the disruptive fault scenario. Could you explain why there is no travel up the disturbed zone and/or vertical section?
A14: There actually is some upflow along the access hole and the associated EDZ. However, this axial flow and radionuclide transport are very small, leading to insignificant releases to the biosphere. The rates are so small mainly because of the inherent design features of the repository system. They include:
(1) There is a considerable horizontal offset (of a few hundred meters) between the disposal section and the vertical access hole.
(2) The trajectory of the repository requires that radionuclides first need to travel horizontally and then vertically, which means you would somehow need driving forces that change direction by a 90-degree angle. Both of these points (offset and orientation) are fundamental differences between the horizontal and vertical borehole concept. In the vertical concept, there is no offset, and the critical upward driving forces (such as thermal expansion, buoyancy effects, and regional upflow) are *aligned* with the repository axis, as opposed to the horizontal concept, where the critical gradients are perpendicular to the repository axis and thus do not promote axial flow.
(3) The vertical access hole is backfilled and sealed, preventing upflow.
(4) The vertical access hole is long because of the depth of the repository, and it's cross-sectional area is much smaller (specifically compared to that of the access ramp or shafts or ventilation tunnels of a mined repository).
(5) In the fault scenario, upflow is driven by the direct connection between the pressurized deep saline formation, the repository, and the surface. Because the repository is located in the shale host rock rather than the saline formation, no such direct connection between the pressurized saline formation and the vertical access hole exists.

(6) There is a qualitative difference between the disturbed zone around the vertical access hole and the disturbed fracture zone of a fault. This is the dimensionality: the access hole is essentially linear, whereas the fault is planar. Moreover, the disturbed zone around the fault is much wider than that around a borehole. Those differences make transport along the access hole path substantially smaller than along a fault plane, even if the permeabilities were similar.

Q15: 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?

A15: We looked at multiple issues related to the source-term model:

(1) We looked at higher and lower waste degradation rates based on data published in the literature;

(2) We looked at the so-called instant release fraction, which means a certain fraction of the iodine inventory has been accumulated in gaps and fractures within the waste form and is released instantly - we used a conservative value of 20% based on data published by Nagra; and

(3) We performed a bounding calculation in which we assumed that (i) the canister 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 (i.e., no solubility limit). We call this the ”instant radionuclide mobilization scenario”. This scenario is obviously unrealistic or even physically impossible and is thus not based on any data. It is just developed to examine how important it is to get the details of the source-term model right. It also shows how effective the natural barrier system is assuming that there is no engineered barrier system at all.

The results of this bounding calculation show that the maximum dose is only slightly increased (by a factor of about 2) by this extreme, unrealistic scenario. It shows that the importance of the *timing* of radionuclide release is insignificant given the already conservatively high waste degradation rate assumed in the reference scenario. The majority of the radionuclides are released after 100,000 years, which is very short compared to the migration time of 1.5 million years; the details of the temporal release are not very influential. This is good news, as residual uncertainties in our understanding of the very complex corrosion and waste degradation processes do not have an undue effect on the results of the safety calculations.

Q16: Could you go into more depth about the initial release of radionuclides in the disruptive fault scenario?

A16: Once the fault cuts through the repository, the radionuclides released in the 50 m wide fault zone are directly transported by advection towards the aquifer. The radionuclides in the disposal section that is not directly affected by the fault would have the possibility to move axially along the drillhole and be flushed out by the water flow within the fault zone. However, such axial flow *towards* the fault intersection is unlikely, as the fault is connected to the overpressured saline formation and is thus at a higher pressure than the repository, so if anything, radionuclides would be pushed *away* from the fault. (If the fault were underpressured, with respect to the repository, flow would be downward, unless the host rock is itself overpressured).

Q17: Could you go into more detail on how you modeled the EDZ in both the Vertical and Horizontal section?

A17: The EDZ is modeled as a ring-shaped zone around the entire length of the drillhole with an axial permeability that is (conservatively) two orders of magnitude higher than the formation it goes through. The thickness of the EDZ is correlated to the radius of the borehole, that is, it gets wider as the borehole gets wider. The EDZ is 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.

Q18: You have shown a repository with a parallel alignment, is this the preferred or required design of the repository? What are the limitations of repository design? What is the expected distance between each borehole and how was this chosen?

A18: There is considerable flexibility in the layout of the repository (parallel, radial, sectoral, vertically staggered, from central drill pad or multiple drill pads, following stratigraphic units, accounting for orientation of stress field, etc. etc.). A specific design should be selected based on site characteristics and pre-closure criteria. The layout described in the report is just one potential configuration; it is considered appropriate for the goals of a generic safety calculation.

Q19: How did you model the amount of radionuclides that would be captured by the near-surface aquifer?

A19: 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 robust safety of the disposal repository.

Q20: Have you modeled disposal of fuel that has just come out of the reactor or has just been cooling for 5 years in the onsite pools?

A20: We have not modeled this specific scenario. However, the main effect of a 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, but 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).

Q21: What was the fraction degradation rate you used and where did you get that rate? Was this based on the dissolution coefficient of uranium oxide?

A21: We used a conservatively high fractional waste degradation rate of 1E-5/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 1E-7/year or lower, depending on the geochemical environment. Note that we also performed a very conservative bounding calculation assuming instant waste degradation, referred to as the “instant radionuclide mobilization scenario”.

Q22: How will the permeability of the overburden rock be measured? How do we ensure a low enough permeability to prevent an aggressive upwards advective transport?
A22: Permeability is routinely determined using geophysical and hydrogeological methods, many of which 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 1E-15 m^2 (1 millidarcy, or 1E-8 m/s) for the overburden and actually see an advective transport component. Nevertheless, the other features of the deep horizontal drillhole repository concept (depth, host rock, geometry, etc.) do not render such a relatively permeable overburden unsafe.

Q23: What is the drillhole diameter?
A23: The diameter of the horizontal waste disposal section of the drillhole 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 drillhole and casing diameters, please see Table 5 in Appendix C of the technical report.

Q24: More discussion 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 1500 canisters; colloidal transport of sorbing radionuclides like Tc-99.
A24: For the current analysis, we selected characteristics of commercial used fuel with an initial enrichment of 4.73%, a burn-up of 60 GWd/MTIHM, and a cooling time of 30 years. Please see A4 and A6 regarding gas generation.
The calculations are based on parallel drillholes 100 m apart from each other (50 m is the distance from the drillhole axis to the symmetry plane between two drillholes). 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 drillholes are the same as those for 1 drillhole (due to symmetry); the dose is approximately inversely proportional to the spacing between drillholes.
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 alluvial deposits near the land surface, 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 an open casing annulus; however, is not considered in the current calculations of a shale repository.