

Safety in depth

The long-term safety of nuclear waste disposal in a generic horizontal borehole repository is evaluated using numerical simulations. Hydrogeologist **Stefan Finsterle** explains the results



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A detailed technical report about the post-closure safety calculations can be downloaded from the Deep Isolation website at deepisolation.com

HOW SAFE IS IT TO dispose of spent nuclear fuel assemblies in a deep horizontal borehole repository? To answer this question, a series of calculations must be presented to determine if the potential future radiation exposure to the public is acceptably low. These calculations must be based on comprehensive and scientifically sound analyses, which are supported by multiple lines of evidence, demonstrating both public safety and that all relevant regulatory safety criteria can be met.

An important component of such a safety assessment is computer modeling in which the long-term progression of the repository system and the transport of radionuclides from the waste canisters to the accessible environment are simulated. Multiple scenarios need to be examined, ranging from the expected response of the engineered and natural barrier systems to an evaluation of the consequences incurred by disruptive, albeit unlikely events. Because such simulations cover very long time periods, and since the conditions and properties of the deep subsurface and man-made materials cannot be known with certainty, it is essential to also discuss the significance of such uncertainties on the estimated exposure risk.

A key safety aspect of geological disposal is the depth of the repository. The overlying formations protect the host rock and waste from the influence of dynamic processes occurring at or near the land surface. Moreover, groundwater flow velocities at depth are very small, and transport distances are long. Consequently, migration times to the surface are long, allowing most of the radionuclide inventory to decay before reaching a drinking water aquifer.

Depths of 1 to 2 km can be readily reached by drilling a vertical access borehole, which gradually turns and eventually follows the near-horizontal layering of a suitable host rock, such as a tight shale formation. Waste canisters, each holding a spent nuclear fuel assembly from a pressurised water reactor, can be placed end-to-end in this horizontal disposal section of the borehole, which has a diameter of less than 0.5m. This deep horizontal borehole concept, proposed by Deep Isolation Inc., is shown in Figure 1. This figure shows a repository consisting of an array of 10 boreholes drilled parallel to each other, spaced 100 meters apart, at a depth of 1km, with 1-km-long horizontal disposal sections. Such a local repository is sufficient to dispose of the waste generated by a 1GWe reactor that has been in operation for 30 years.

Model development

The computer model was developed based on a symmetry cell containing one of the disposal boreholes. The borehole and its various components (ie the waste, canisters, backfill, casing, cement and an adjacent excavation disturbed zone) are accurately represented by a radial-axial

submodel that follows the hole's trajectory. This borehole model is embedded in a three-dimensional geosphere model, which consists of a deep saline formation, the shale that hosts the horizontal disposal section of the borehole, an overburden and a near-surface aquifer from which drinking water is extracted. A subvertical fault — assumed to be reactivated during a large earthquake — is included for the analysis of a disruptive seismic event scenario. The middle panel of Figure 1 is a visualization of this model.

Appropriate hydrogeological and thermal property values are chosen to describe each of the geological and man-made materials. The conditions at the time of repository closure also are specified. The initial pressure profile is approximately hydrostatic, assuming the groundwater table is at the land surface, and accounts for density effects due to changing temperature and salinity, both of which increase with depth. Next, radionuclides are selected based on their potential relevance for repository safety. These are likely radionuclides that have a long half-life (such as I-129), a large inventory (such as Tc-99), high mobility (such as Cl-36), or high toxicity (such as Se-79 and I-129) or a combination of these characteristics. The amount of each of these safety-relevant radionuclides present in the waste at the time of disposal is specified. This inventory is slowly released into the borehole as the waste degrades and the canisters corrode. The decay heat emanating from the waste is also included in the model as a time-dependent heat source.

The computer model is able to simulate relevant flow and transport processes. These simulated processes, which are described mathematically, include: the release of selected radionuclides from the waste canister; their migration (by both diffusive and advective transport mechanisms) in saline groundwater along the backfilled borehole and into the geological formations; and their mixing with groundwater in the aquifer and eventual extraction from the drinking water well. Finally, the radiological effects on a person drinking contaminated water is evaluated. The maximum exposure occurs long after repository closure. To make sure the peak dose is captured by the model, the simulation is run to a time of ten million years.

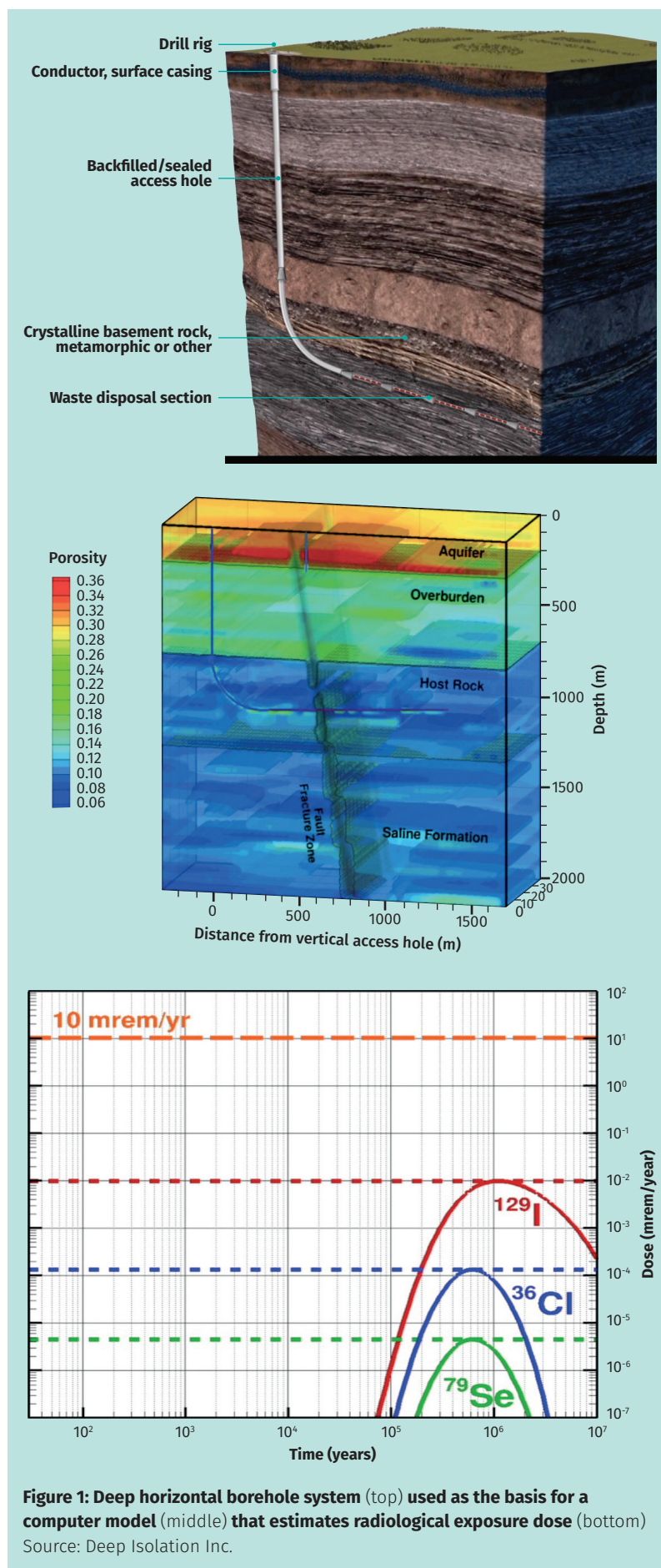
Simulation results

The curves shown on the bottom panel of Figure 1 indicate that radionuclides first arrive at the drinking water well after about 100,000 years, albeit in very small concentrations with insignificant dose effects. The exposure dose increases slowly with time and reaches its peak value after more than 1.5 million years. The peak dose is dominated by the radionuclide I-129; contributions of the other radionuclides are insignificant. (Note that Tc-99 never makes it to the aquifer, as it readily is absorbed by the solid

particles of the rock formations and is effectively immobilised.) The calculated peak dose value is approximately 0.01 millirems per year (or 0.0001 millisieverts per year), which is 1000 times smaller than a typical regulatory dose standard of 10 millirems per year.

This is an encouraging result. However, it can only support the safety argument if the scenario can be considered realistic and relevant, and if the simplifying assumptions that the simulations are based on are not chosen in an optimistically biased way. To examine the robustness of the results to factors that are unknown or uncertain, additional simulations are performed. These include sensitivity analyses, in which individual parameter values are changed (such as the ability of the rocks to transmit water) or major assumptions are modified (such as the existence of an overpressured formation beneath the repository, pushing contaminated water upwards). Moreover, disruptive scenarios are formulated (such as the activation of a fault, or the early failure of canisters) to see how strongly the calculated dose would be affected by such unlikely events. Bounding calculations are performed, in which extreme parameter values or extreme assumptions are examined (such as the instant degradation of the waste and canisters and complete dissolution and mobilisation of the radionuclides). The results of such bounding calculations are unrealistic or even physically impossible, but nevertheless useful to better understand the barrier function or behaviour of a particular component of the repository system. Finally, probabilistic analyses are used to propagate the uncertainty in model input parameters (such as property values, but also initial and boundary conditions, source terms, and parameterised aspects of the conceptual model) through the model to estimate the uncertainty in the calculated exposure dose.

Figure 2 illustrates the results of such a probabilistic analysis. The sampling-based Monte Carlo method was used, in which parameter values are randomly picked from given uncertainty distributions and then randomly combined into a set of model input parameters. These are then used to calculate the dose curve based on the computer model described above. This procedure is repeated multiple times, so that the resulting uncertainty in the calculated exposure dose can be described statistically, for example by histograms or percentiles. Exposure dose curves were calculated for 400 realisations of uncertain model input parameters. Calculated peak dose values range widely (over approximately six orders of magnitude). However, only peak doses at the high end of the distribution are of interest. For example, just 5% of the realisations yield peak dose values that are higher than 0.1 millirems per year. The earliest time when peak dose is



Below: **Figure 2:**

Lower-left: **Median exposure dose curve (blue line) and dose curves from 400 randomly sampled realisations of uncertain model input parameters (red lines)**

Upper-left: **Histogram of peak dose times with statistical parameters**

Lower-right: **Histogram of peak dose with statistical parameters**

reached is about 100,000 years; the median is at about 1.5 million years.

This initial probabilistic safety analysis indicates that while the calculated annual dose is uncertain, the peak dose — even for the most unfavourable parameter combination considered — remains well below the typical dose standard of 10 millirems per year. This suggests that the results are fairly robust and that despite considerable uncertainties, there is no indication that a deep horizontal borehole repository sited in a shale host rock cannot meet even stringent safety requirements.

Final thoughts

Scientists, engineers, regulators, elected officials, other stakeholders and the public need to feel confident in the safety of a horizontal borehole repository. This can only be achieved through a comprehensive performance assessment study. While waste disposal in horizontal boreholes is a novel concept, its components and implementation procedures are solidly based on established technologies and processes. Moreover, many aspects of the proposed concept can benefit from decades

of research, testing, engineering analyses and worldwide experience by independent institutions, nuclear waste management organisations, as well as by the oil, gas and geothermal industries.

The post-closure radiological consequences, calculated using a simplified representation of a generic deep horizontal borehole repository located in shale, show that the estimated maximum annual dose is low and that this dose estimate is robust to changes in key assumptions and uncertainties in the model parameters. Furthermore, the calculations suggest that the overall safety goal of isolating the waste from the accessible environment is inherently supported by the depth of the repository and the attributes of its configuration. Long-term confinement of radionuclides in the stable waste matrix and long migration times allow for radioactive decay to occur within the repository system, considerably reducing the activity of radionuclides potentially being released to the accessible environment.

The calculations summarised here are generic, that is, they do not derive from a specific geographic location or geological site. Consequently, the positive evaluation of the horizontal borehole disposal concept is preliminary and is only transferrable if the geological environment at an actual disposal site exhibits characteristics that are similar to those assumed in these calculations, and if the repository is carefully constructed, operated and sealed as is assumed in the simulations. It is understood that repository performance has to be reassessed as site-specific information becomes available. Nevertheless, generic calculations such as those presented here are considered a useful if not necessary step toward developing a comprehensive, site-specific safety analysis. They also serve as a basis for successive stages in repository planning, siting and development, and they provide a sound platform for interactions with interested parties and stakeholders. ■

