Article

Disposal of High-Level Nuclear Waste in Deep Horizontal Drillholes

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Abstract: Spent nuclear fuel and high-level radioactive waste can be disposed in deep horizontal drillholes in sedimentary, metamorphic, or igneous rocks. Horizontal drillhole disposal has safety, operational, and economic benefits: The repository is deep in the brine-saturated zone far below aquifers in a reducing environment of formations that can be shown to have been isolated from the surface for millions of years; its depth provides safety against inadvertent intrusion, earthquakes, and near-surface perturbations; it can be placed close to the reactors and interim storage facilities, minimizing transportation; disposal costs per ton of waste can be kept substantially lower than for mined repositories by its smaller size, reduced infrastructure needs, and staged implementation; and, if desired, the waste could be retrieved using "fishing" technology. In the proposed disposal concept, corrosion-resistant canisters containing unmodified fuel assemblies from commercial reactors would be placed end-to-end in up to 50 cm diameter horizontal drillholes, a configuration that reduces mechanical stresses and keeps the temperatures below the boiling point of the brine. Other high-level wastes, such as capsules containing ^{137}Cs and ^{90}Sr, can be disposed in small-diameter drillholes. We provide an overview of this novel disposal concept and its technology, discuss some of its safety aspects, and compare it to mined repositories and the deep vertical borehole disposal concept.

Keywords: nuclear waste isolation; horizontal disposal drillholes; directional drilling; engineered barrier system, spent nuclear fuel, waste repository, geologic disposal; high level waste.

1. Introduction

We present a novel repository concept for the disposal of spent nuclear fuel and high-level nuclear waste. The concept consists of an array of deep horizontal drillholes bored into suitable sedimentary, igneous, or metamorphic host rocks using off-the-shelf directional drilling technology. Waste is encapsulated in specialized corrosion-resistant canisters, which are placed end-to-end into the relatively small-diameter, cased and backfilled horizontal disposal sections of the drillholes. A schematic representation of a deep horizontal drillhole repository is shown in Figure 1. The concept allows for consolidated waste disposal in a national or a few regional repositories, or decentralized disposal in modular, smaller repositories located at or near the reactor sites or processing plants where the waste was produced.

44
45   (a)

46
47   (b)   (c)
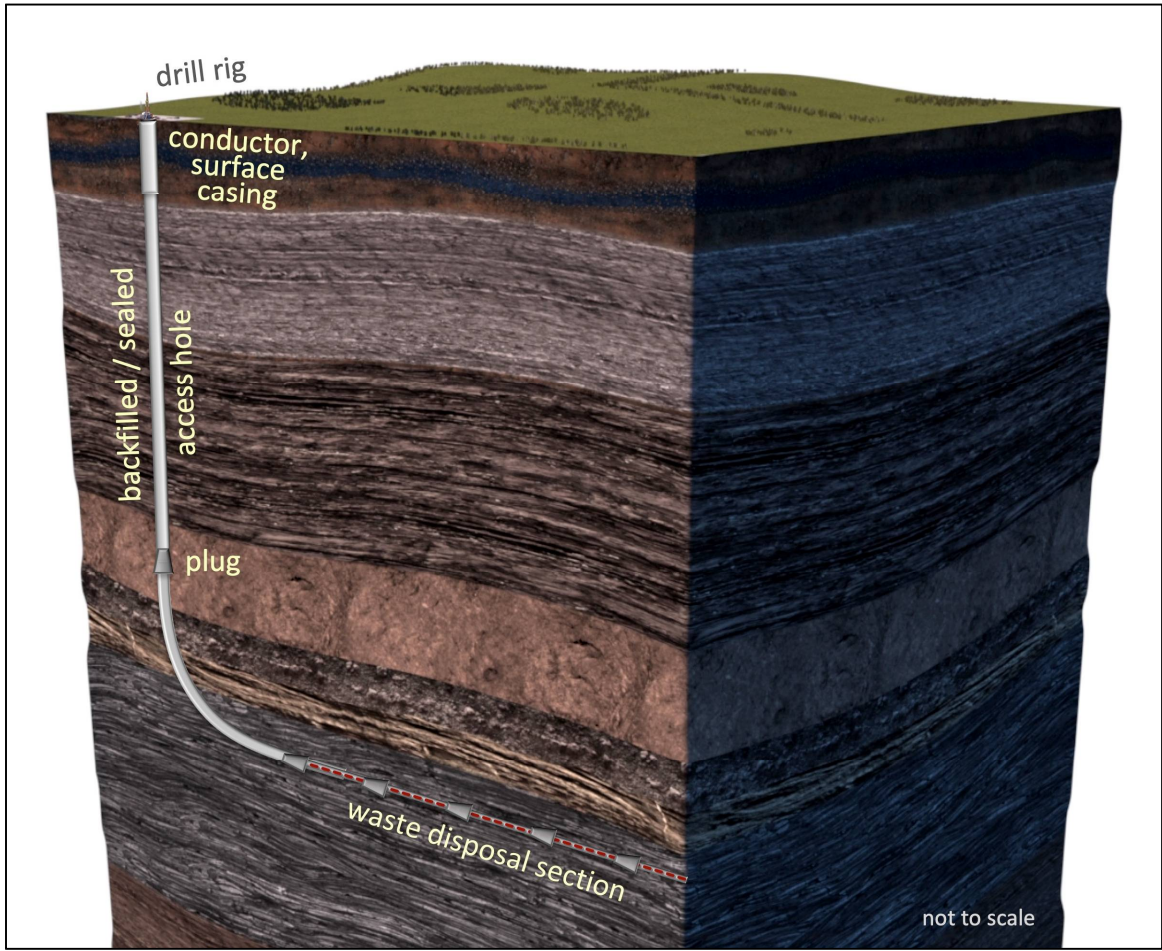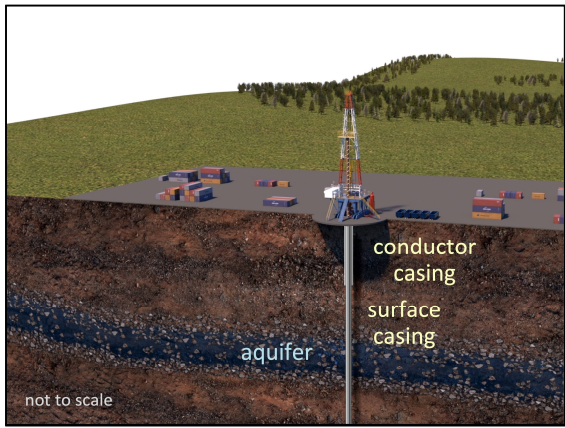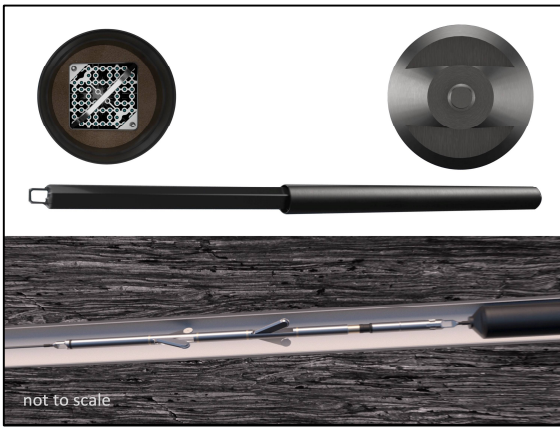
48   **Figure 1.** Schematic of a deep horizontal drillhole repository (not to scale); (a) a vertical access hole is
49   drilled to the kickoff point below confining layers, where the hole is gradually curved until it is
50   approximately horizontal. It then continues for a few hundred meters to several kilometers; this near-
51   horizontal part of the drillhole is the waste disposal section of the repository, where canisters holding
52   individual spent nuclear fuel assemblies are emplaced end-to-end, before the drillhole is plugged and
53   sealed; (b) multiple casings provide stability, protect aquifers, and guide waste canister emplacement;
54   (c) spent nuclear fuel assemblies are placed into canisters which are capped; a tractor is used to push
55   the canister into the horizontal disposal section of the drillhole.

56   High-level nuclear waste comes in many forms; we focus here on two types: (1) the small
57 capsules of concentrated cesium and strontium (Cs/Sr) defense waste [Forsberg et al., 2000], and (2)
58 the spent nuclear fuel (SNF) from commercial nuclear reactors [EIA, 2019]. Other waste forms, such
59 as the granular solids of calcined high-level waste at the Idaho Nuclear Technology and Engineering
60 Center [Staiger and Swenson, 2011], or the borosilicate glass of vitrified high-level waste in the Glass
61 Waste Storage Buildings at the Savannah River Site [SNL, 2014], may also be considered for disposal
62 in a horizontal drillhole repository, but are not further discussed in this paper. The drillhole disposal
63 concept takes advantage of the fact that nuclear waste is very compact. The following discussion
64 refers to the current waste inventory in the United States.

65   The Cs/Sr defense waste is a by-product of chemical processing of spent fuel from nuclear
66 reactors used for plutonium production, and from reactors that were part of the U.S. Navy nuclear
67 fleet. Because of the relatively short half-life of ^{137}Cs and ^{90}Sr (about 30 years), which results in high
68 radioactivity and high heat generation, these isotopes were extracted from the spent fuel in the form
69 of cesium chloride (^{137}CsCl) and strontium fluoride (^{90}SrF$_2$), placed in about 2,000 double- and triple-
70 walled capsules [Price, 2016] and stored at the Hanford Waste Encapsulation and Storage Facility in
71 Richland, Washington. (Note that the capsules also contain minor amounts of the much longer-lived
72 ^{135}Cs isotope.) To dispose of all Cs/Sr capsules, only about 2 km section of a small-diameter, horizontal
73 drillhole would be needed.

74   The commercial spent nuclear fuel currently consists of approximately 80,000 tons of ceramic
75 UO$_2$ pellets [EIA, 2019]. A total of about 280,000 SNF assemblies discharged from both pressurized
76 water reactors (PWR) and boiling water reactors (BWR) are presently held at about 75 sites in 33 states
77 [Wagner et al., 2012]. About two-thirds of the waste is in cooling pools at the power plants, and one-
78 third has been transferred to dry casks, which are cooled by gas flow rather than by immersion in
79 water. In the coming years (until a permanent disposal solution becomes available), the fuel
80 remaining in pools will gradually be moved to dry casks, usually at the same location, or possibly at
81 a consolidated interim storage facility [NRC, 2019]. Placing SNF canisters (each containing a single
82 PWR or BWR assembly) into drillholes end-to-end every 6 m (accounting for variable canister lengths
83 and some spacing between them) amounts to a total disposal-section length of 1,680 km (1,050 miles),
84 i.e., on average about 22 km (14 miles) for each of the 75 current storage sites. Table 1 summarizes the
85 number and dimensions of individual waste units, the diameter of a disposal canister, the required
86 casing and drillhole diameters, and the total length of horizontal disposal sections needed.

87   **Table 1.** Geometry of waste and required drillhole dimensions [Price, 2016; Wagner et al., 2012;
88   Carter et al., 2014; SNL, 2014].

Waste type [1]	Number [2]	Capsule or Assembly		Disposal canister ID [5]	Casing ID [5]	Drillhole diameter	Total disposal section length [6]
		diameter [3] (cm)	length [4] (cm)	(cm)	(cm)	(cm)	(km)
Cs	1,335	6.6–8.3	55	10	13	15	1.4
Sr	601	6.6	53	10	13	15	0.6
BWR	~160,000	16–23	440	20–27	25–32	32–40	960
PWR	~120,000	23–31	409	27–35	32–40	40–48	720

89   [1] Waste types: Cs – cesium-137 capsules; Sr – strontium-90 capsules; BWR – boiling water reactor
90   assemblies; PWR – pressurized water reactor assemblies.
91   [2] Approximate number of spent nuclear fuel assemblies as of 2019; the number increases by approxi-
92   mately 4,000 BWR and 3,000 PWR assemblies per year.
93   [3] Diameters of capsules and assemblies vary depending on manufacturer.
94   [4] Average assembly length.
95   [5] ID – inner diameter; casing and drillhole diameters are typically given in inches (1 inch = 2.54 cm);
96   standard drill bits [Baker Hughes, 2019] and casing sizes [Weatherford, 2019] can be used for the
97   construction of the proposed drillhole repository.
98   [6] Approximate total length of horizontal disposal sections, assuming each canister contains a single
99   capsule or fuel assembly, and accounting for spacing between canisters.

100   Horizontal drillhole disposal has become feasible and attractive because of the technological
101   development of advanced directional drilling in the last two decades. A typical oil or gas well has an
102   inner diameter from 5½ to 8¾ inches (14 to 22 cm), which is sufficiently wide to accommodate Cs/Sr
103   waste capsules. As mentioned above, SNF disposal in unmodified assemblies requires drillholes with
104   a diameter of up to 19 inches (48 cm). The technology for directional drilling of such large-diameter
105   boreholes exists [Baker Hughes, 2019]. In the U.S. alone, there are over 50,000 drillholes with a
106   horizontal section of 3 km or longer and a depth of 1 to 5 km.
107   Disposal of radioactive waste in deep drillholes is not a new idea. It was evaluated as early as
108   1957 by the U.S. National Academy of Sciences [NAS, 1957]. The deep borehole disposal option
109   discussed in that report considers the injection of liquids containing highly diluted waste into deep,
110   permeable formations, i.e., a concept very different from what is proposed here. In 1979, a report to
111   the U.S. Atomic Energy Commission [O'Brian et al., 1979] outlined the possibility of waste disposal
112   in up to 6 km deep shafts and up to 15 km deep boreholes. The report evaluates geotechnical,
113   geophysical, environmental and safety issues, discusses data adequacy, and identifies research and
114   development needs. Technical feasibility was further examined in a report commissioned by the
115   Office of Nuclear Waste Isolation (ONWI) [Woodward-Clyde, 1981]. In 1989, [Juhlin and Sandstedt,
116   1989] concluded that waste disposal in very deep boreholes (6 km) drilled into the crystalline
117   basement rock in Sweden was considered both feasible and economical. The scheme proposed by
118   Gibb [2000] and Chapman and Gibb [2003] makes use of the decay heat generated by the high-level
119   waste to partially melt and then recrystallize the granitic host rock in the bottom disposal section of
120   a 5 km deep borehole. (Similar concepts involving rock melting and self-burial of the waste have been
121   proposed as early as 1974 [Logan, 1974].) In 2003, the interdisciplinary MIT study on the future of
122   nuclear power [Ansolabehere et al., 2003] recommended that deep borehole disposal be investigated
123   as an alternative to mined repositories. Starting in 2009, the vertical borehole disposal concept was
124   further examined by Sandia National Laboratories [Brady et al., 2009; Bates et al., 2014], and a
125   reference design was developed [Arnold et al., 2011]. The project was expanded by the U.S.
126   Department of Energy (DOE) in 2012, when an experimental program and demonstration project was
127   initiated [SNL, 2016]. (Note that the deep borehole disposal program was canceled by the Department
128   of Energy in 2017.) The Blue Ribbon Commission on America's Nuclear Future considered deep

129   borehole disposal a potentially promising technology that should be pursued [BRC, 2012]. In 2015,
130   the Nuclear Waste Technical Review Board (NWTRB) dedicated one of its board meetings to technical
131   presentations and discussions of the deep borehole disposal concept [NWTRB, 2015]. Finally, a
132   review of European deep borehole disposal programs can be found in Nirex [2004] and Sapiie and
133   Driscoll [2009].

134   These earlier concepts consider vertical boreholes, or boreholes that are only slightly tilted to
135   enable multiple disposal sections to be constructed from a single drill pad or as laterals from a main
136   access hole [Chapman and Gibb, 2003]. The horizontal drillhole concept discussed in this paper is
137   briefly mentioned [Sapiie and Driscoll, 2009; NWTRB, 2015], but not examined in any detail. While
138   waste disposal in vertical and horizontal boreholes appears very similar, these two concepts are quite
139   different in their technical requirements and performance (see Section 4.2 below).

140   The safety of high-level radioactive waste disposal in horizontal drillholes mainly stems from
141   the depth of the repository, and therefore, the effectiveness of the natural barrier system, which
142   consists of thick, confining rock strata with very low hydraulic conductivities and low diffusivities,
143   resulting in extremely long radionuclide travel times to the surface. In addition, there is a sequence
144   of effective components of the engineered barrier system, which includes (1) the ceramic UO_2 fuel
145   pellets, (2) the zircaloy cladding of the assemblies, (3) any material that fills the spaces within the
146   canisters, which (4) are made of corrosion-resistant alloy, (5) the buffer material between the canister
147   and the casing, (6) the carbon steel casing, and (7) the cement or other filling between the casing and
148   the drillhole wall. The engineered barrier system also includes (8) plugs and (9) backfill materials that
149   seal the vertical access hole. The compactness of the small-diameter access and disposal sections of
150   the drillhole repository strengthen these engineered components and reduce their vulnerability.

151   Finally, construction costs of drillhole repositories are expected to be considerably lower than
152   those for conventional mined repositories, mainly because of the drastically reduced excavation
153   volume, the use of off-the-shelf equipment for drilling and waste emplacement, the simplicity of the
154   engineered barrier system, the potential avoidance of repackaging and transportation, and the fact
155   that no ancillary infrastructure is needed to support humans working underground. Moreover, the
156   modular concept allows for staged, fast implementation and immediate closure, thus reducing the
157   considerable costs for interim storage and operation of an open repository.

158   The main purpose of this paper is to describe the concept of using deep horizontal drillholes for
159   decentralized, permanent, cost-effective disposal of high-level radioactive waste. The technical
160   description of the concept (Section 2) is followed by a general discussion of the expected repository
161   performance (Section 3). We compare deep waste isolation in horizontal drillholes with alternative,
162   complementary concepts, such as mined repositories—specifically at Yucca Mountain, Nevada, the
163   site designated for the disposal of spent nuclear fuel and other high-level radioactive wastes in the
164   United States—and the deep vertical borehole disposal concept (Section 4). The proposed concept's
165   main advantages and challenges will be discussed in Section 5. Note that detailed assessments of the
166   horizontal drillhole concept will be presented in separate technical papers.

167   **2. Deep Horizontal Drillhole Disposal Concept**

168   *2.1. Radioisotope Inventory*

169   We begin the description of the repository concept with some general remarks about the waste
170   that needs to be disposed of, focusing on SNF assemblies. The nuclear fuel pellets inserted into a
171   reactor are made of UO_2, with about 96% ^{238}U and 4% ^{235}U. Because of the long half-lives of ^{238}U and
172   ^{235}U (4.5 and 0.7 billion years, respectively), the radioactivity of the fresh fuel rods is low. However,
173   once in the reactor, the situation changes. When uranium fissions, it splits into two or more fission
174   fragments, which are typically very radioactive due to their much shorter half-lives. Most of the ^{235}U
175   generates decay products such as ^{3}H, ^{90}Sr, ^{137}Cs, ^{129}I, and ^{99}Tc. In addition, some of the ^{238}U is converted
176   by neutron absorption and decay into transuranics such as ^{239}Pu, ^{240}Pu, ^{241}Am and ^{237}Np. Other
177   isotopes are created by the decay of their respective parent radionuclides, and their concentrations
178   may actually increase as time passes.

179   It is worth noting that the radioisotopes with very short half-lives decay quickly and thus cause
180   little long-term concern. In contrast, isotopes with very long half-lives (such as ^{238}U and ^{235}U) decay
181   so slowly that they have low radioactivity. It is the isotopes with intermediate half-lives (such as ^{137}Cs
182   and ^{90}Sr) that are difficult to handle and that present disposal challenges. These fission fragments are
183   responsible for most of the high intensity of the SNF's initial radioactivity; later, after the first few
184   centuries, the transuranics contribute most of the long-lived radioactivity.

185   The initial isotope inventory of the nuclear waste to be disposed in a geologic repository is a key
186   determinant of the overall risk. The abundance of each isotope, its half-life, and that of its daughter
187   products along the decay chain determine the radioactivity and toxicity of the waste. However, the
188   key performance measure of a repository is not the waste inventory in the canisters, but the dose
189   received by a reasonably maximally exposed individual at the surface. This means that the release of
190   isotopes from the waste containers and their transport through the engineered and natural barrier
191   systems to the accessible environment have to be accounted for. The mobility of radioelements is
192   influenced by many factors (such as the flow of liquids and gases, the radioelement's solubility,
193   adsorption behavior, diffusivity, and volatility). These are properties of both the radioelements
194   themselves as well as the man-made and geologic materials through which they migrate.
195   Consequently, the importance of a given radionuclide in the context of nuclear waste disposal is the
196   product of its abundance and an index that accounts for all factors governing the fate of the
197   radionuclide from the waste canister to the affected individual [Jarzemba and Pickett, 1995]. These
198   importance factors can only be determined by a comprehensive performance assessment analysis,
199   which requires detailed design information and site-specific characterization data. Nevertheless, it is
200   important to have a detailed waste inventory available as input to such an assessment; the inventory
201   developed for the Yucca Mountain project [Miller, 2004] is thus pertinent for a drillhole repository in
202   the United States.

203   Although the spent fuel from a commercial nuclear reactor could be repackaged or reprocessed,
204   we currently assume that it will be kept in the same assemblies that held it in the nuclear reactor. In
205   reactor operations, each fuel assembly is handled as a unit. It typically spends 3 to 5 years in a reactor,
206   at which time it is replaced with an assembly containing fresh fuel. During refueling, the reactor is
207   shut down, the lid of the reactor is removed, and one fuel assembly at a time is moved to a cooling
208   pool. Even though the chain reaction has stopped, the initial heat production of the removed fuel
209   assembly is almost 7% of that during reactor operation. As the short-lived radioisotopes decay, so
210   does the rate of heat production. After ten minutes it has decayed to 2% of the operating power, and
211   after a day to about 0.5%. As more of the radionuclides decay, the heat production decreases further;
212   after 1 year it is about 10 kW per ton of spent nuclear fuel; after 10 years, it is about 3 kW per ton. The
213   impact of heat generation on repository performance is discussed in Section 3.5.

214   *2.2. Drillhole Repository Configuration*

215   The overall configuration of a horizontal drillhole repository has been schematically presented
216   in Figure 1 above. A vertical access hole is drilled and cased from the surface through confining
217   geologic units to a kickoff point a few hundred meters above the target repository horizon. The
218   purpose of the conductor and surface casings are, respectively, to guide the drilling and to protect
219   freshwater aquifers, schematically shown in Figure 1b. In the horizontal disposal section, the casing
220   facilitates the emplacement (and potential retrieval) of the canisters and supports backfilling opera-
221   tions. A smaller-diameter hole is gradually curved, with a build angle of less than 0.25° per meter (8°
222   per 100 feet), until it is horizontal. The radius of curvature is large enough to avoid any impedance
223   during casing installation and waste emplacement. A third set of casing is installed and cemented in
224   place and then yet a smaller diameter drillhole then continues near-horizontally for a few hundred
225   meters to several kilometers. This part of the drillhole is the waste disposal section of the repository,
226   having a diameter as shown in Table 1 to accommodate the canister size designated for a given
227   drillhole. Drilling technology has advanced to the point where rotary steerable systems have high
228   precision with absolute and relative accuracy of less than 1 m.

229   As the hole is being drilled, rock cores, fluid samples, and formation evaluation well logs are
230   collected to aid in site characterization and emplacement decisions. For larger-diameter canisters, the
231   horizontal section may be drilled in two stages: a first small-diameter stage for evaluation and testing
232   of the disposal section followed by a reaming operation to create a diameter large enough to house
233   the canisters.

234   Once the horizontal section is drilled, another string of casing is cemented in place, potentially
235   with monitoring systems embedded on or in the casing that communicate real-time data about the
236   repository condition to the surface. The continuous casing in the curved and horizontal section of the
237   drillhole facilitates the emplacement (and potential retrieval) of the canisters and supports backfilling
238   operations. Moreover, the casing and the surrounding cement act as additional engineered barriers
239   during the early periods after waste emplacement, providing mechanical protection and preventing
240   fluid flow around the canisters during the initial equilibration phase. The casing also effectively
241   redistributes heat, reducing temperature gradients and associated thermal stresses.

242   Several drillholes may be completed from the same surface pad, either using separate vertical
243   access holes, or possibly by drilling multiple laterals (potentially at different depths) from a single
244   access hole. Modular drillhole repositories could be constructed at or near the sites where the waste
245   is currently in interim storage, minimizing or even avoiding the need for waste transportation outside
246   the boundaries of the nuclear facility. Alternatively, larger, regional repositories could be built if
247   considered appropriate for technical reasons or if otherwise preferred.

248   The nominally horizontal repository section may have a slight tilt. Such a tilt of a few degrees
249   may be beneficial in keeping fluids and dissolved radionuclides from migrating towards the vertical
250   access hole by inducing density- or buoyancy-driven fluid gradients towards the dead-end of the
251   drillhole.

252   *2.3. Waste Emplacement*

253   To prepare for disposal in a drillhole, the assemblies will be removed from cooling pools or
254   temporary dry storage casks, and each one placed in a canister made of a corrosion-resistant alloy.
255   To simplify the transfer of SNF from dry casks to permanent disposal, a new cask storage design
256   could be developed, in which fuel assemblies sitting in the cooling pools are directly loaded into
257   disposal canisters, before being placed into a concrete cask for dry storage.

258   The canisters are sealed and transported to the drill rig. These operations require radiation
259   shielding by using a transport cask or a modified dry cask system. The canisters are then lowered
260   into the casing and pushed (using a wireline tractor, coiled tubing, or drill pipe [Bates et al., 2011;
261   Beswick et al., 2014]) into the horizontal disposal section, where they are released. Canisters may be
262   emplaced one-by-one, or in strings of multiple canisters to reduce round-trip time.

263   In the event of a canister breaking free from its support cable and falling into the vertical access
264   hole, there are several mitigating measures that can be devised to reduce or prevent damage to the
265   canister or casing. The falling canister's terminal velocity is limited by the presence of water, brine,
266   or other viscous fluids present in the casing. For a heavy canister, however, that velocity might be
267   high enough to allow the canister to reach a speed which presents danger to the integrity of the canis-
268   ter, specifically if it hits another canister that had previously been put in place. The maximum velocity
269   can be substantially reduced by self-deploying breaking devices, such as an expandable centralizer,
270   a parachute mechanism, or the use of foams. Damage from a collision can also be mitigated by the
271   use of an impact absorber placed on the front end of the canister [Hardin et al., 2016]. Should a
272   canister be damaged, a procedure has to be in place to de-contaminate the drillhole and associated
273   equipment.

274   Another emplacement risk is that a canister may get jammed or otherwise stuck above the
275   disposal section due to the casing's tortuosity, or other irregularities or obstructions. The large radius
276   of curvature and the precision of current rotary steerable drilling technology make the risk of canister
277   sticking or jamming during the emplacement process very low. However, to further mitigate this
278   risk, a caliper or dummy canister can be lowered into the drillhole to ensure that the casing is free of
279   obstacles and that the emplacement equipment functions as intended. Tools and procedures to

280 retrieve a stuck canister from the drillhole have been routinely used for oil and gas operations and
281 can be enhanced for nuclear disposal operations.

282 *2.4. Retrievability*

283 Many countries require that nuclear waste be retrievable after placement in a repository (in
284 current U.S. law, this is regulated in 10 CFR 60.111, requiring retrievability for "up to 50 years after
285 the waste emplacement operations are initiated" or "until the completion of a performance confirma-
286 tion program"). Retrievability was mandated, in part, because of the possibility that a better disposal
287 method or site might later be found, or that the nuclear waste could have value in the future (e.g., as
288 fuel for next-generation nuclear reactors).

289 To facilitate canister recovery, one option would be to leave the vertical access drillhole open for
290 the first 50 years. Note, however, that sealing of the hole does not preclude recovery, as plugged
291 boreholes can be reopened. In the drilling industry, recovery of objects in a deep drillhole is consid-
292 ered routine using "fishing" technology [DeGeare, 2015]. Placement and retrieval of borehole
293 equipment are highly developed in the oil industry and are commonly performed using wireline
294 with a tractor, coiled tubing, or drill-pipe methods.

295 On November 15, 2018, we placed a dummy canister in a 690 m deep horizontal drillhole,
296 released it, withdrew the placement cable, and several hours later inserted a recovery cable, latched
297 the canister, and brought it back to the surface. This test was carried out under contract by a drilling
298 company at a previously drilled horizontal borehole. The procedure was repeated on January 16,
299 2019 as a demonstration [Conca, 2019].

300 The size and weight of the dummy canister used in the test was designed to represent a canister
301 holding a Cs/Sr capsule. The canister was attached to a hanger, which had a releasable connector; the
302 hanger was attached to a tractor with electrically-driven retractable wheels that pushed against the
303 casing. The tractor was linked to the surface with a wireline cable. The canister was lowered in the
304 vertical section to the kickoff depth at 242 m. From that depth the hole gradually turned until it was
305 horizontal at a depth of 690 m. The tractor pushed the canister 122 m into the horizontal section. The
306 canister and hanger were released, and the wireline cable and tractor were withdrawn to the surface.
307 Subsequently, a special latching device was installed at the end of the tractor and the assembly
308 lowered into the drillhole. The tractor pulled the assembly back into the horizontal section. The
309 latching mechanism engaged the canister-hanger combination, and the canister was pulled back to
310 the surface.

311 Although this initial demonstration was successful, retrievability of canisters from the disposal
312 section needs to be further examined for the larger SNF canisters and for conditions prevalent in a
313 backfilled, heated, potentially sealed disposal section. A comprehensive bibliography of reports
314 discussing retrievability can be found in NEA [2010].

315 *2.5. Canister and Casing*

316 The canister holding the spent nuclear fuel assemblies or other high-level radioactive waste is a
317 key component of the engineered barrier system. The canister directly protects the waste from
318 mechanical impact, exposure to the chemical environment, and contact with fluids, which dissolve
319 the waste and act as the main transport vehicles for radionuclide migration. While radionuclides
320 released from a breached canister (at early times) will very likely remain contained within the multi-
321 barrier repository system, it is obviously desirable to use canisters with long-time durability. We
322 propose to fabricate canisters made of highly corrosion-resistant nickel-chromium- molybdenum (Ni-
323 Cr-Mo) alloys, such as Alloy 22 (UNS N0622) [Special Metals Corporation, 2019a] and Alloy 625 (UNS
324 N06625) [Special Metals Corporation, 2019b], which are very stable in the expected hot, reducing
325 chloride environments representative of the deep drillhole disposal sections. Elevated temperatures
326 affect the corrosion behavior of the canister, because they impact both corrosion resistance of the
327 metals and corrosivity of the environment. In the passive state, metals are protected by a thin, self-
328 forming film on the surface, leading to very low general corrosion rates (on the order of 0.01 μm/y).

329   A canister made with Alloy 625 with a wall thickness of 1 cm takes at least 50,000 years to degrade
330   by general corrosion [Payer et al., 2019].
331   Localized corrosion mechanisms, which are a particular threat to the durability of passive films,
332   need to be accounted for when predicting the lifetime of a canister [King and Kolář, 2019]. The Ni-
333   Cr-Mo alloys, with their durable protective (passive) films that are self-forming even in harsh
334   environments, have robust resistance to the localized corrosion processes of pitting, crevice corrosion,
335   and stress corrosion cracking [Rebak, 2006; Shoesmith, 2006; King, 2013; Payer et al., 2019]. High
336   durability of the passive film on Ni-Cr-Mo alloys results from a combination of resistance to film
337   breakdown even in highly aggressive environments and the ability to reform (repassivate) after it has
338   been damaged. Microbially induced corrosion (MIC) is another potential damage mode to canisters.
339   Alloy 22 is not only among the most-resistant alloys for abiotic corrosion mechanisms, but is among
340   the most resistant to MIC [King, 2009]. The MIC resistance of Alloy 22 and titanium alloys has been
341   examined under a range of conditions with no evidence of surface damage [Else et al., 2003]. Galvanic
342   corrosion is an additional damage mode to be considered, and its effects will depend upon the other
343   metals incorporated in the repository, the relative surface areas and the conductivity of filler materials
344   and pore waters.
345   Mechanical breaching of the canister, for example by puncturing during handling and
346   emplacement, or shearing during seismic events or crushing by rock consolidation or volcanism,
347   should also be considered. These risks are mitigated to some extent by the strength of the canister
348   wall.
349   Calculations for carbon steel casings indicate that their lifetime in a reducing environment can
350   reach several hundred years [Payer et al., 2019]. This is long enough to provide a reliable and
351   relatively smooth conduit for canister retrieval, should that become necessary or worthwhile. While
352   casings are not designed for long-term waste protection, it is beneficial to have a barrier restricting
353   fluid flow during the early pressure equilibration and thermal periods.
354   The corrosion of the canisters and casing forms metal oxides and generates hydrogen gas. Both
355   processes lead to volume expansion and, consequently, pressure increases, which in turn induce fluid
356   flow. The use of corrosion-resistant materials leads to a slow generation of corrosion products
357   (hydrogen and oxides). Outside the containment, the slow gas generation allows most of the
358   hydrogen to dissolve in the liquid and diffuse away, i.e., reducing or avoiding the emergence of a
359   free gas phase [Finsterle et al., 2019]. Moreover, generating corrosion products from a linearly spread-
360   out source expedites radial diffusion and dissipation of the pressure perturbation.

361   *2.6. Backfilling and Sealing*

362   Open space within the canister, between the canister and the casing, the casing and the drillhole
363   wall, as well as along the vertical and curved access sections of the drillhole will be backfilled. The
364   repository may be further sealed by plugs. One of the potential pathways for radionuclides to reach
365   the accessible environment is through advective transport along the drillhole and the excavation
366   disturbed zone around it. Backfilling and sealing these preferential pathways is thus of primary
367   importance.
368   Each backfill material will be designed for a particular purpose or specific barrier function. In
369   general, low hydraulic conductivity, durability, and self-healing abilities are among the main desira-
370   ble characteristics of a backfill material. However, the choice of material is limited by the engineering
371   challenges of installing the backfill in a small-diameter, deep drillhole. Backfill and sealing methods
372   considered in the deep borehole disposal reference design are described in Arnold et al. [2011] and
373   Arnold et al. [2014].
374   As mentioned above, the annulus between the casing and the drillhole wall should be filled
375   using cementitious materials with formulations currently used by the hydrocarbon and geothermal
376   energy industries. Cementing is important to stabilize the casing during canister emplacement and
377   to keep the casing centralized, which is necessary to reduce thermal stresses. Using fine-grained
378   cements and other permeation grouts also helps seal the excavation disturbed zone.

379   Excess space inside the canister can be filled with a suitable material to provide additional safety
380 against damage from impact and vibration during emplacement or an earthquake, and to increase
381 thermal conductivity for more efficient heat dissipation. This filler could also include boron to absorb
382 neutrons and lower the risk of reaching criticality (see Section 3.9).
383   Once emplaced in the disposal section, backfilling the space between the canisters and the casing
384 serves multiple purposes, including providing stability and mechanical protection, increased heat
385 conduction, reduced fluid flow and, therefore, reduced advective transport of leaked radionuclides.
386 It also helps to control the chemical environment, inhibiting corrosion and increasing the adsorption
387 of radionuclides.
388   Compacted, expandable bentonite is the backfill material of choice in most mined repositories
389 located in the saturated zone (for a review, see Selling and Leupin [2013]). However, the excellent
390 barrier properties of bentonite can only be realized if installed under unsaturated conditions,
391 allowing the clay to expand as it hydrates. In a deep drillhole, installation of dry granular bentonite
392 or bentonite blocks is infeasible. Nevertheless, the use of a high-density bentonite suspension is a
393 possibility to be considered. The requirement for pumpability limits the options to materials that set,
394 gel, solidify, or swell after emplacement, either driven by a chemical process, temperature changes
395 or mechanical compaction, which induces creep flow or visco-plastic deformations. Such backfills
396 include cementitious materials, oil-based materials (such as tar, bitumen, or asphalt), pumpable
397 colloidal silica and other grout mixtures, salts, or fine pellets of lead-based alloys that melt and re-
398 solidify to encapsulate the canisters [Gibb et al., 2008]. A detailed research and engineering program
399 could help select or adapt these materials to the chemical, thermal, and stress environment at the
400 repository site. Moreover, verifiable methods will be needed to install the backfill material in a small-
401 diameter drillhole and to examine its as-built performance.
402   When canister emplacement is complete and all initial performance confirmation tests yield
403 satisfactory results, the disposal section is plugged and the vertical access hole is backfilled and
404 sealed. Effective plugs may be installed by reaming the drillhole over a relatively short section that
405 is preferably located adjacent to a clay, shale or salt rock layer. The reamed drillhole section will be
406 filled with a suitable backfill material, which will be compacted by the overburden and plastic
407 deformation of the surrounding rock [Kristiansen et al., 2018; Vrålstad et al. 2019], effectively isolating
408 the disposal section from the surface and at the same time sealing the excavation disturbed zone.
409 Similar plugs may be installed throughout the disposal section to compartmentalize the disposal
410 section, reducing the risk of axial radionuclide transport to transmissive zones that may intersect the
411 drillhole. In the vertical hole sections that penetrate deformable formations, the casing or liner may
412 be removed after waste emplacement to promote self-sealing. Rock welding with resistance heaters
413 and ceramic plugs have also been proposed [Lowry et al., 2015]. The as-built effectiveness of a plug
414 may be confirmed by performing an in-situ pressure test [Fjær et al., 2018]. However, the long-term
415 stability is difficult to assess; multiple plugs may be installed along the drillhole for redundancy.
416   Backfilling of the disposal, curved, and vertical sections of the drillhole provides an opportunity
417 to add sorption-enhancing amendments that retard radionuclide transport; a similar concept has
418 been proposed for the invert in the emplacement tunnels at Yucca Mountain [Krumhansl et al., 2006].
419 Backfilling and plugging might increase costs but should not compromise the ability to retrieve waste
420 canisters. Finally, the sealing procedure has to account for the incorporation of sensors that may be
421 installed for performance confirmation.
422

3. Expected Repository Performance

3.1. Basis of Performance Evaluation

Nuclear waste disposal in deep horizontal drillholes is a novel concept. While work on the detailed repository design and performance assessment is ongoing, an initial evaluation of the expected repository performance builds on the extensive research, analyses, developments, and experiences of many organizations throughout the world that develop high-level nuclear waste repositories (for a review, see Faybishenko et al. [2016]). Of particular significance is the work that has been performed to assess the performance of mined repositories in a reducing, fully saturated environment—specifically those located in argillaceous host rocks—as well as deep borehole disposal concepts. Complete performance assessments are available for mined repository concepts; a generic safety case for a deep borehole disposal scenario is presented in Freeze et al. [2013]. The following subsections discuss some performance aspects on a general level, with specifics being addressed in the cited references and upcoming publications.

3.2. Leakage Pathways

The performance of a nuclear waste repository is ultimately measured by the exposure risk to individuals. Evaluating this risk requires a deterministic or probabilistic assessment of the fate and transport of radionuclides from the waste form in the repository along some leakage pathway to the receptor. This pathway is part of several subdomains referred to as (1) the engineered barrier system (EBS), which includes the waste, canister, backfill, and other engineered components, such as liners and seals, (2) the geosphere, also referred to as the far field or natural barrier system, which includes the host rock and aquifers, and (3) the biosphere, which is the biological environment that determines the radiation dose to the receptor [Freeze and Vaughn, 2012]. Special consideration is given to the interface between the EBS and the geosphere, which consists of the damaged or disturbed zone around the excavation [Bénet et al., 2017].

It is essentially impossible to anticipate all potential failure modes and leakage pathways, and to determine their probability, characterize the relevant properties, and predict the consequences over the entire performance period. Inserting redundancies into a multi-barrier system and making realistically conservative assumptions in the performance assessment calculations are safeguards used against the inherent uncertainties and unidentifiable variabilities of a complex repository system. In this overview, we mention just a few leakage pathways that need to be considered when evaluating the performance of a deep horizontal drillhole repository.

In Section 2.5, we briefly mention the role that the canisters play in protecting the waste during the initial, critical period after emplacement up to about 50,000 years [Payer et al., 2019]. After a breach of the canister (either by corrosion or mechanical destruction, e.g., during earthquake-induced fault reactivation), radionuclides dissolve into the resident brine and are released to the near field either by diffusion or advective and dispersive transport. This sequence of processes constitutes the so-called source term. The release rate from the canister may be limited by the solubility or the diffusivity of the radionuclide, along with the geometry of the canister perforation. The reducing conditions encountered in a deep, saturated formation tend to lower the solubility of most radionuclides, leading to smaller release rates and thus lower contaminant concentrations.

Once released from the canister, the radionuclides start migrating (either by advection or diffusion) within and across the engineered barrier system. Given the low permeability of the host rock, radionuclides may preferentially be transported in axial direction along the drillhole. Transport velocity is expected to be very low, mainly because of (1) the presence of low-permeable, absorbing backfill material, (2) plugs installed to prevent axial flow towards and within the vertical access hole, and (3) the absence of significant driving forces. The last point deserves additional comments. Potential driving forces within the drillholes are either created by the repository itself, or imposed by the natural system. Gradients induced by the repository include differences in chemical potential driving molecular diffusion, pressure perturbations caused by the decay heat (i.e., thermal expansion and contraction of fluids and the pore space during the heat pulse), pressure increases caused by

473   corrosion (i.e., volume increase due to the generation of oxides and hydrogen gas), and general
474   equilibration of drilling- and emplacement-induced pressure perturbations. All of these forces are
475   expected to be minor, limited in time, and acting axially over the restricted cross-sectional area of the
476   small-diameter drillhole. Consequently, radionuclide mass flow rates along the drillhole are expected
477   to be very small.
478   Gradients in the natural system include (1) regional pressure differences caused by topography
479   and recharge patterns, (2) thermal upwelling or convection cells, (3) pressure perturbations induced
480   by stress redistribution (e.g., after an earthquake, volcanic eruption, or due to erosion, uplift, or
481   glacial loading), and (4) the development of osmotic pressures across rocks with high clay content.
482   Most of these gradients are expected to be small, or they develop—and dissipate—slowly over
483   geologic times. Notable exceptions are earthquakes and volcanism. Such disruptive events may
484   generate new faults or magmatic intrusions, or reactivate old faults. These discrete features may
485   directly intersect the drillhole and impact the integrity of the engineered barrier system. At the same
486   time, they provide potential pathways for fluid flow and radionuclide transport. Also note that
487   seismic and igneous events may impact pressure gradients even if they occur at a considerable
488   distance from the repository.
489   Finally, pressure gradients may be generated by human activity, specifically by nearby hydro-
490   carbon production or by large-scale geologic carbon sequestration and energy storage projects.
491   The migration of volatile radionuclide-containing species such as $^{14}CO_2$ can occur in near-surface
492   repositories located in the unsaturated zone [Sullivan and Pescatore, 1994; Moeller et al., 2006].
493   However, this is very unlikely in the case of a deep drillhole repository located within the saturated
494   zone, where high fluid pressures inhibit the generation of a free gas phase and its migration through
495   the rock.
496   A site- and disposal hole-specific hydrogeological characterization of the host rock as well as the
497   overlying units and cap rocks will determine the properties of the heterogeneous formations,
498   specifically their ability to transmit water in response to the local and regional pressure gradients
499   discussed above. Particular attention needs to be given to the geometric and hydrological characteris-
500   tics of faults, deformation zones, contacts between hydrostratigraphic units, and fracture networks.
501   Nevertheless, the relatively great target depth (>1 km) of the horizontal drillhole repository makes it
502   unlikely that long, continuous natural pathways exist or are created, or that they have sufficient
503   permeability, cross-sectional area, and sustained driving forces to induce significant upward flow
504   rates over long time periods. Radioelement retention properties, such as adsorption onto mineral
505   surfaces and diffusion into stagnant pore water in the surrounding rock matrix, would retard their
506   transport to the accessible environment. Finally, the fact that nuclear waste emplacement is
507   decentralized and stretched out linearly in multiple drillholes (rather than placed with high density
508   at a centralized location) significantly decreases the amount of waste likely to be affected by a
509   disruptive event.
510   For disposal sections located in competent rock of low matrix permeability, molecular diffusion
511   of dissolved radionuclides is the only remaining transport mechanism, albeit with very small
512   migration rates. Diffusion is driven by chemical-potential gradients, which decrease substantially at
513   even short distances from the disposal drillhole. The small porosity and tortuosity of the pore space
514   considerably reduce the effective diffusivity compared to that in free water. Diffusing radionuclides
515   reach very low concentrations after short distances as they are diluted and spread over a radially or
516   even spherically increasing volume of pore water.
517   Initial calculations lead us to believe that the assessments comprising the safety case will likely
518   demonstrate that these features and effects have either very low probabilities of occurrence or low
519   consequences, or that they do not compromise the safety of the repository even when making
520   conservative assumptions and accounting for inherent and irreducible uncertainties. The horizontal
521   drillhole disposal concept takes advantage of geological formations with very high barrier perfor-
522   mance, integrated into a robust disposal system with multiple engineered barriers. Similar screening
523   decisions as the ones presented here have been made previously based on a generic analysis of
524   features, events, and processes (FEPs) [Hansen et al., 2010].

3.3. Isolation of Brines from Aquifers

The disposal section of the horizontal drillhole repository is to be located in a deep formation whose pore space would most likely be saturated with brine. Demonstrating that such a brine has been isolated at depth for long time periods is a key factor in assessing the long-term security of the repository. Establishing the absolute age of brines is complicated by mixing processes and the lack of an ideal chronologic marker in the water. However, various isotopic systems can help place limits on age and mixing rates.

In addition to numerical modeling, a good indicator of isolation could be determined by measuring the presence of radioisotopes such as ^{81}Kr. ^{81}Kr is a rare gas formed by cosmic ray interactions in the atmosphere and then incorporated into surface waters. Since it has minimal interaction with local rock and is not generated at depth in significant amounts, it can provide a direct measurement of the isolation of deep brines from surface waters. The presence of measurable ^{81}Kr (with a half-life of 201,000 years) in repository brines indicates that significant amounts of surface water are interacting with or replacing brines on a time scale less than one million years. Conversely, the absence of ^{81}Kr in brines suggests isolation of the brines over similar time scales. Concentrations of ^{81}Kr are extremely small (hundreds of atoms per liter); however, a laser-based resonance ionization technique measures this isotope with sufficient sensitivity [Chen et al.,1999; Buizert et al., 2014]. Note that low mixing of surface water with deep brines does not directly demonstrate that there is equally slow transport upward.

Upward flow limits can be estimated by measurements as a function of depth of other isotopes including ^{36}Cl, and ^{129}I. These can be measured in deep brines from about liter of sampled using AMS (accelerator mass spectrometry) [Muller, 1977]. These radioisotopes are produced naturally underground through the decay of uranium and thorium in the rock strata. In the absence of significant flow, each isotope maintains a natural background concentration in the rock that balances production and decay, a pseudo-steady state referred to as secular equilibrium. It takes approximately 4 to 5 half-lives for the system to reach this stable background concentration. These values can be predicted based on the measured rock composition and calculated or measured neutron fluxes from samples [Fabryka-Martin, 1988; Phillips, 2013]. Successive layers of rock strata that maintain distinct and different secular equilibrium concentrations of these radio-isotopes indicate limited upward flow [Cornett et al., 2010]. We focus here primarily on ^{36}Cl, which has a half-life of 300,000 years, and ^{129}I which has a half-life of 16 million years. Maintenance of unique ^{36}Cl secular equilibrium concentrations can place limits on upward flow of Cl through the rock strata on time frames on the order of one million years. As a simple example, if an overlying formation has a lower value of ^{36}Cl or ^{129}I than does an underlying layer, that suggests absence of significant upward flow of these isotopes.

Helium gas analysis offers another independent means to assess upward flow. ^{4}He, the stable isotope of helium, are emitted in alpha-decay. The balance of production and escape of ^{4}He from the rock strata determines the residence time of helium in the rock. ^{4}He gas is quite mobile and estimates of residence times for ^{4}He on the order of 100,000 years and greater suggest that other less mobile species in brines should not escape the rock strata over similar or more likely much longer time frames [Gautschi, 2001].

In all of these isotopic studies, care must be taken to keep samples pristine. Small amounts of contamination from field sampling and in the laboratory can yield inaccurate and misleading results. Despite inherent difficulties, successful measurements of these isotopes in diverse settings and field conditions are now routinely undertaken.

In addition to isotopic methods, the confining properties of the overburden may be demonstrated by the presence of trapped gas in layers above repository strata. If it is determined that the natural gas was formed over millions of years earlier, then the existence of such gas provides strong evidence that the brine in deeper layers is not flowing upwards.

574   *3.4. Reducing Environment*

575   As mentioned above, the reducing environment encountered at repository depth is beneficial
576   for the longevity of the waste canisters and casing. In addition, it affects the solubility and, therefore,
577   the mobility of radionuclides in the subsurface.
578   In the event a canister is breached, and the spent nuclear fuel is exposed to the brine saturating
579   the host rock, the constituents of the waste can react with the brine and form new compounds of
580   varying solubility. The subsequent advective and diffusive migration of dissolved radionuclides is
581   dependent on their chemistry, that of the host rock, and the dissolved constituents in the brine.
582   Furthermore, most of these factors depend on temperature, alkalinity, and redox potential.
583   The chemical factors that determine the extent of radionuclide migration can be divided into two
584   groups, namely (1) those that immobilize the radionuclide by adsorption, ion exchange, or mineral
585   (co-)precipitation, and (2) those that govern complexing of cationic radionuclides with anions
586   dissolved in the brine, which may enhance their solubility and thus make them amenable to
587   transport.
588   The valence state of several radionuclides can differ depending on the ambient oxidation state,
589   and in those cases, their chemical properties and ability to migrate can be substantially affected. All
590   of the above processes are in competition, and predicting the actual migration of any given radio-
591   nuclide depends on integrating the critical thermodynamic and kinetic parameters affecting its
592   solubility, which needs to be carefully examined by means of reactive transport modeling, and if
593   necessary, supported with additional experiments.

594   *3.5. Decay Heat*

595   The temperature evolution in and around a drillhole containing heat-generating high-level
596   radioactive waste is an important factor impacting repository performance. It affects corrosion rates,
597   barrier properties of backfill materials, degradation of concrete, fluid density and viscosity,
598   radionuclide solubilities, the evolution of the excavation disturbed zone, and biogeochemical reac-
599   tions; in summary, temperature is a key driver of many coupled processes.
600   The radiation from the spent nuclear fuel is converted to heat in the waste, the engineered
601   barriers and the rock. The decay heat for Cs/Sr waste is initially up to 400 W per capsule [Price, 2016],
602   decreasing with a half-life of about 30 years. The decay heat for spent nuclear fuel depends on the
603   initial enrichment, burnup percentage, and duration of post-reactor cooling. An initial value for spent
604   nuclear fuel is on the order of 10 kW per metric ton of heavy metal (MTHM) [Ansolabehere et al.,
605   2003], decreasing with time as the initial radionuclide inventory and its daughter products decay, as
606   shown in Figure 2 for SNF from a PWR reactor.
607   The temperature of the canister and the rock around it initially rises before declining as the
608   radioactivity falls, and as the rock continues to conduct heat away. As an example, Figure 3 shows
609   the temperature evolution around a drillhole holding Cs/Sr capsules that are emplaced with a 2-feet
610   (0.6 m) spacing between them. The initial heat output is 100 W; the temperature change, ΔT, shown
611   in Figure 3 can be linearly scaled to different initial heat output values, and can be converted to
612   absolute values by adding the ambient temperature of the host rock. Although the maximum
613   temperature (reached after about 3 years) is above the boiling point of water at atmospheric condi-
614   tions, it is well below the boiling point for water at a depth of 1.0 km below the water table, which is
615   about 310 °C. These simulations are described in detail in Finsterle et al. [2019]; similar studies for
616   Cs/Sr capsules in water, air, and deep vertical boreholes are presented in Arnold et al. [2014].
617   These analyses suggest that the linear arrangement of waste canisters with relatively low energy
618   density combined with an approximately cylindrical heat dissipation regime decreases the risk of
619   excessive temperature perturbations, both within the disposal section of the drillhole and the adjacent
620   host rock. Most importantly, boiling is suppressed by the high hydrostatic pressure, drastically
621   reducing the adverse effects of steam on repository components and lowering the complexity of
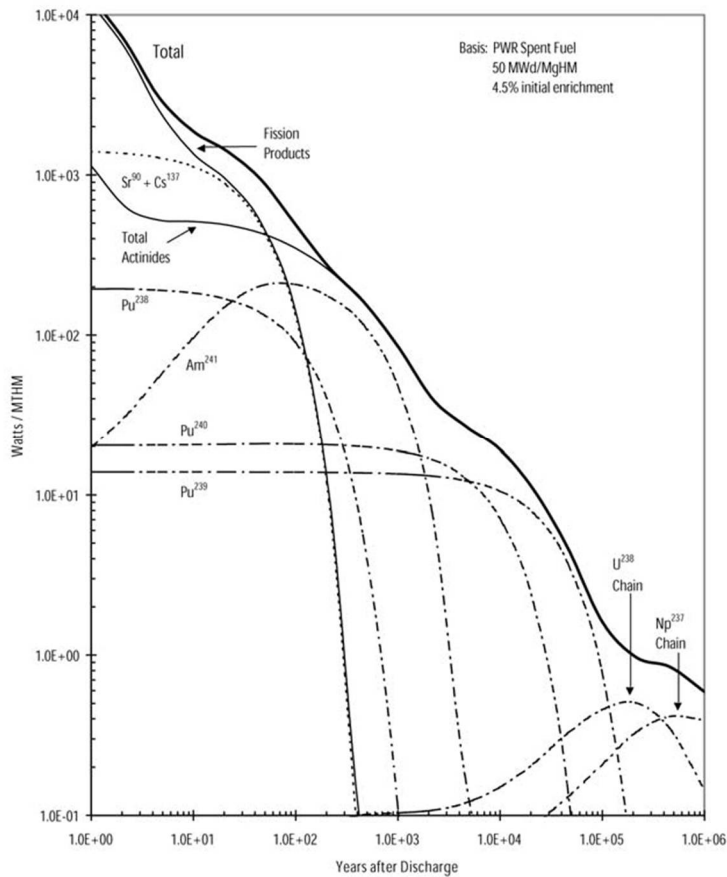622   predicting the overall system behavior.

623

624   **Figure 2.** Decay heat profile of spent fuel [Ansolabehere et al., 2003].
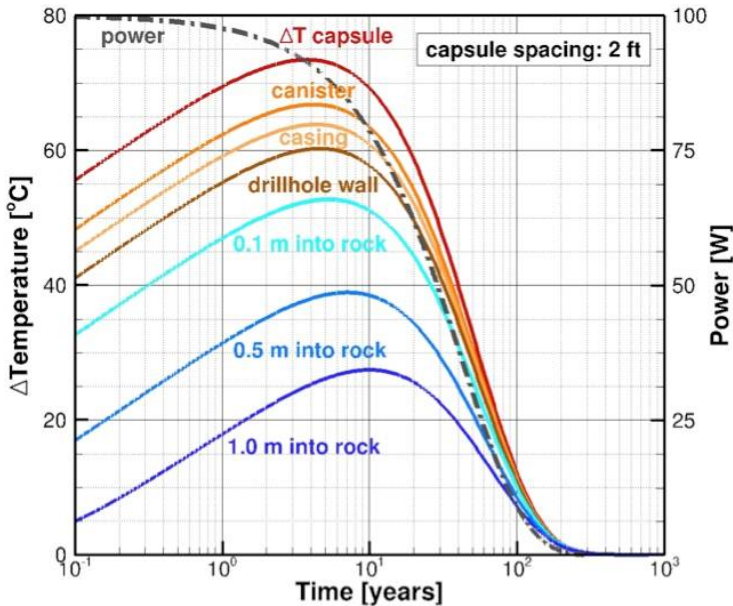
625

626   **Figure 3.** Evolution of temperature change and decay-heat output for an initial heat release of 100 W
627   per waste capsule with a capsule spacing of 2 ft. (0.6096 m) [Finsterle et al., 2019].

628   *3.6. Earthquakes*

629   The following two effects of earthquakes on the integrity of the drillhole repository are consid-
630   ered: (1) potential damage to the engineered barrier system, and (2) the creation of new pathways for
631   radionuclides to reach the accessible environment.

632   The potential damage to a canister from earthquake vibrations is small. The only examples of
633   vibration-induced borehole damage occur in highly unconsolidated sediments, which are not
634   suitable for a repository. Near the surface, accelerations of earthquakes rarely exceed 1 *g*, where *g* is
635   the gravitational acceleration; below the surface, accelerations are considerably smaller [Bäckblom,
636   2002]. At early times, the casing and cement also substantially attenuate earthquake vibrations due
637   to the elastic impedance contrasts between the rock, the cement and the casing. The fuel rods are held
638   within the canister by the structure of the fuel assemblies and the filling material, and the canisters
639   are embedded in their respective backfill materials and a cemented-in casing.
640   There is the possibility that one or several canisters will be sheared by a new fault or by reactiva-
641   tion of an existing fault. The probability of a fault actually cutting the repository is very low and can
642   be further reduced through site and drillhole characterization methods and by orienting the drillholes
643   sub-parallel to the direction of existing faults, so that the shear stress is unlikely to create a new fault
644   that crosses the drillhole. A standoff distance of 100 m from an active fault is sufficient to mitigate the
645   risk of damage to the drillhole. Moreover, for most types of rock, the ductility of the canister is greater
646   than that of the rock, and for small fault offsets, the canister would rotate or deform rather than
647   rupture. For some rocks, such as granite, shearing may occur, albeit only affecting a very small
648   number of canisters, even though secondary fracturing and faulting may extend to a distance on the
649   order of 100 m perpendicular to the main fault plane.
650   Finally, as mentioned in Section 3.2, the creation or reactivation of a fault or associated fracture
651   zone might also create new pathways for fluid flow and radionuclide transport, along with earth-
652   quake-induced pressure perturbations acting as the driving force. It should be noted, however, that
653   many faults are not water conducting, and the induced pressure gradients are transient.
654   While strong earthquakes lead to high accelerations and substantial rupturing at and near the
655   land surface, these effects decline with depth, where rock strength increases and no surface wave
656   exists, limiting the impact of earthquakes on the engineered barrier system in a deep drillhole. More-
657   over, a modular, decentralized waste disposal concept reduces the risk that a large number of
658   canisters are breached in a single event.

659   *3.7. Criticality*

660   Criticality refers to the risk that stored fuel will undergo a sustained chain reaction, made
661   possible, perhaps, from the intrusion of water that could serve as a neutron moderator. There is no
662   danger of criticality for the Cs/Sr waste, which is very low in ^{235}U or ^{239}Pu content. Estimating the
663   probability of SNF reaching criticality will require the use of computer simulations [Anttila, 1999]. It
664   can be noted, however, that the spent fuel rods are low in ^{235}U or ^{239}Pu—the very reason why they
665   were removed from the reactor. They could still deliver energy in an environment in which most
666   neutrons are created by fissions in other fuel rods. However, in a drillhole repository, they are placed
667   in a linear configuration, not side-by-side as in the reactor. The empty space in canisters holding the
668   fuel assemblies will be filled with a sand-like material, limiting the volume of water that may be
669   present. If deemed necessary, neutron absorbers (such as boron) could be added to the filler.
670   Nevertheless, for certain kinds of defense waste, particularly those containing high levels of
671   plutonium, the criticality issue will have to be carefully evaluated.

672   *3.8. Inadvertent Intrusion*

673   Inadvertent intrusion refers to the accidental drilling into a repository during the exploration for
674   water or mineral resources. The deep horizontal drillhole concept offers inherent protection against
675   inadvertent intrusion, mainly because of its location well below potable water resources.
676   Furthermore, the flexibility in siting modular horizontal drillhole repositories allows their placement
677   in regions with no commercially viable natural resources. The probability may be higher in regions
678   that have oil or gas bearing shale at the same geographic location. For the short term, this issue is
679   addressed by the U.S. Nuclear Regulatory Commission (NRC) regulations that require mineral rights
680   be secured at any location where nuclear waste is disposed. Finally, U.S. regulations mandate that a
681   marker be placed above the site to alert future generations of the presence of the repository [Trauth

682   et al., 1993]; the effectiveness of such markers, however, is difficult to demonstrate, and the
683   consequences of inadvertent intrusion needs to be evaluated regardless of the efficacy of the markers.

684   *3.9. Terrorist Intrusion*

685   Unlike interim storage in pools or dry casks on or near the land surface, waste disposal in deep
686   geologic repositories provides a geologic barrier that gives significant protection against a terrorist
687   attempt to obtain spent nuclear fuel. Although the fuel is retrievable, removing even one canister
688   after sealing of the vertical access hole requires setting up a tall rig, removing several hundred meters
689   of drillhole sealant, and operating a specialized system to pull up each canister. Although this
690   procedure is feasible for a professional service company, it is not inexpensive or quick. Moreover, the
691   retrieved canisters will be radioactive when they come to the surface, requiring terrorists to rig
692   shielding and safety equipment. Removal of radioactive waste from a deep drillhole does not lend
693   itself to a surreptitious terrorist attack.

4. Comparison with Other Repository Concepts

4.1. Mined Repositories

The worldwide predominant waste disposal concept is to construct tunnels and caverns in a suitable host rock (igneous, metamorphic, sedimentary, or salt) at a depth between 300 m and 900 m, and to emplace specially designed disposal canisters holding the waste directly in these mined cavities, or in short vertical or horizontal deposition holes excavated in the floor or sides of a network of access drifts. For repositories located in the saturated zone, highly compacted bentonite is typically used as the buffer within the deposition holes; access tunnels are backfilled and plugged. Variations of this general repository layout are described by Faybishenko et al. [2016].

There are important differences between a mined repository and the proposed deep horizontal drillhole concept, some of which can be summarized as follows:

- *Defense in Depth* — The currently proposed mined repositories are relatively shallow (typically 500 m) compared to the intended depth of the horizontal disposal section of a drillhole repository (> 1,000 m). While suitable host formations can be found at shallow depths (note that these sites would also qualify for horizontal drillhole repositories), the option to explore deeper has considerable advantages. It expands the rock volume and number of locations available for potential repository siting. More importantly, it increases isolation of the waste, because (1) the thick overburden with multiple confining layers considerably augments the natural barrier system, (2) the migration distance to the accessible environment (especially drinking-water aquifers) is increased substantially, (3) the rock at depth is more competent, and hydrogeological conditions are more stable and less affected by the dynamics of near-surface processes, and (4) the likelihood of inadvertent intrusion is considerably smaller. Since long-term safety is one of the main goals of any disposal solution, the ability to rely on the natural barrier system is paramount. Going deeper makes best use of the natural barrier system, which is the essence of geological disposal of nuclear waste.

- *Size and Geometry* — The volume of rock that needs to be excavated for a mined repository is substantially larger than that for a drillhole repository. Large-diameter access ramps that are long (due to their limited slope) or shafts are needed for a mined repository, whereas a small-diameter, vertical or curved access hole is sufficient to reach the waste emplacement horizon. Reducing the diameter of the disposal section increases the stability of the opening. More importantly, it reduces the overall hydrological, chemical, and mechanical perturbation of the host rock, specifically the extent of the excavation damaged zone, which is considered a potential pathway for radionuclide leakage. The cross-sectional area available for axial radionuclide transport along the backfilled opening and associated damage zone is also much smaller. Sealing deposition holes, constructing plugs, and backfilling large access tunnels is more challenging and less reliable than sealing small-diameter drillholes. Finally, the linear end-to-end emplacement of small-diameter canisters holding individual SNF assemblies leads to a smaller waste density, with beneficial consequences for heat dissipation, corrosion-gas accumulation and diffusion, and impacts from canister breaches, earthquakes, and volcanism. Lower waste density and higher heat dissipation efficiency allows for waste disposal after short post-reactor cooling times at the surface and immediate site closure (i.e., no need for extended ventilation periods); it also reduces post-closure criticality issues.

- *No Humans Underground* — Much of the excavation volume and infrastructure of a mined repository is needed for enabling humans to work underground. This includes drainage and ventilation of the tunnels, but also the installation of transportation and emergency equipment. Large machinery for excavation and waste emplacement require additional infrastructure. Humans will need to work underground during the construction of the repository, its operation and closure. This requires continued drainage and ventilation of the tunnel system until repository closure, i.e., typically for a few decades. In many cases, ground support systems or liners must be installed. In addition to costs, changing the underground conditions to those needed for human life considerably affects the near field of the repository. Drainage over decades leads to

fluid flow in the host rock and depressurization with associated deformations caused by effective stress changes. Ventilation not only leads to dry-out and potential desiccation cracking (in a clay-rich host rock), but introduces oxygen that remains underground until consumed by corrosion and other chemical reactions. While most of these perturbations are limited in time, some may be irreversible and need to be accounted for, complicating performance assessment calculations. While waste emplacement in a mined repository may be accomplished using remote-controlled machinery, the process of doing so is complex and costly. By comparison, constructing a drillhole repository and waste emplacement in the disposal section has minimal impact on the hydrology, geochemistry, and stress conditions of the host rock. The perturbations that do occur are of considerably smaller extent and shorter duration. Construction, waste emplacement, and site closure activities are simpler and require fewer workers and no underground support system. These factors contribute to the lower costs of a drillhole repository.

- *Site Characterization* — Information and data from site characterization activities are key for site selection and performance assessment calculations and eventual licensing of a repository. While much of the initial characterization is done from the surface (e.g., using geophysical methods) and exploration boreholes drilled proximate to the disposal borehole, humans working in a mined repository have direct access to the host rock for detailed characterization and testing. For a drillhole repository, such direct inspection of the host rock by humans is limited to cores pulled from the drillhole. Nevertheless, testing, mapping, and characterizing rock properties from boreholes is off-the-shelf technology in the hydrocarbon and geothermal industries. Extensive data sets can be obtained from cores, fluid samples, geophysical well logs, borehole videos, caliper logs, hydraulic and compliance testing, in-hole tracer testing, flowing fluid electric conductivity logging, and high-resolution, continuous monitoring of temperatures, deformations, and acoustic signals using fiber-optic cables [Arnold et al., 2011]. Sophisticated methods and computational toolsets for analyzing and interpreting borehole data are available. It should also be noted that direct underground observations available in mined repositories are limited to the tunnel surface, which is a very small fraction of the three-dimensional host formation. Moreover, the properties inferred from these observations reflect the excavation disturbed zone (which is much smaller and thus less relevant in a drillhole repository), and they may be biased due to the artificial environment created in the tunnel. For example, ventilation effects bias or render impossible the direct observation of water inflows that would occur under natural conditions. The need to account for such unwanted effects greatly complicates the analysis and interpretation of "direct" observations taken in a mined repository [Finsterle and Pruess, 1995; Ghezzehei et al., 2004].

- *Modularity* — Mined repositories are typically conceptualized as large, centralized facilities, intended to accommodate all or a considerable fraction of a country's high-level nuclear waste inventory. For such large projects, site selection, licensing, construction, waste emplacement, and site closure are all technically challenging, expensive, and time-consuming processes with a considerable risk of failure—for both technical and non-technical reasons. Deep horizontal drillhole repositories are suitable for flexible, modular, decentralized, and fast implementation. Finding disposal solutions for a relatively small fraction of the waste (e.g., that produced by a nearby power plant or other nuclear facility) is more tractable. Long-distance transportation of nuclear waste can be reduced or eliminated altogether. Surface facilities are relatively small, and the duration of an individual project comparatively short. Customized solutions for special conditions (e.g., small inventories) or special types of waste (e.g., the Cs/Sr capsules) can be found and implemented in a locally optimized, timely manner. We also believe that stakeholders are more amenable to accept a local solution that substantively reduces the risks associated with local interim storage at the surface and long-distance transportation.

Key differences between a mined repository and the deep horizontal drillhole concept are listed in Table 2.

796   **Table 2.** Comparison between a minded repository and the proposed deep horizontal drillhole
797   repository.

Feature	Mined Repository	Horizontal Drillhole Repository
depth	0.3–1.0 km	>1 km
access hole diameter	3–8 m	<0.5 m
deposition hole diameter	1.5–5.0 m	<0.5 m
excavation volume	large	small
ground support	shotcrete/rockbolts/wire mesh	casing/liner
drainage and depressurization	yes	no
ventilation	pre- and post-emplacement	no
workers underground	yes	no
local waste and heat density	high	low
temperature limit	~100 °C (bentonite)	in situ boiling temperature
implementation	later	earlier
repository closure	>50 years	immediately
retrievability	yes	yes
costs	high	low

798

799   The Yucca Mountain mined repository is unique in that it is located in the unsaturated zone, i.e.,
800   above the groundwater table. While the previous general comments about mined repositories (and
801   their differences to a deep drillhole repository) also apply to Yucca Mountain, there are some
802   additional features specific to Yucca Mountain that are worth discussing:

803   • *Unsaturated Zone* — The pores of the fractured, volcanic rocks at the Yucca Mountain repository
804   level are only partly filled with water. (Note that aridity was one of the main reasons why Yucca
805   Mountain was selected as a potential disposal site [McKelvey, 1976]). Even given that the liquid
806   saturation of the tuff matrix is typically above 80% [Bandurraga and Bodvarsson, 1999], air flows
807   primarily within the fracture network [Ahlers et al., 1999; Unger et al., 2004]. One consequence
808   of ubiquitous airflow is that volatile radionuclides may be transported to the atmosphere
809   [Sullivan and Pescatore, 1994; Moeller et al., 2006]. However, the main consequence of the
810   presence air convection is that the repository is in an oxidizing environment, substantially
811   affecting water chemistry and its impact on canister corrosion and radionuclide solubility. The
812   considerable benefits of a repository located in a reducing environment have been discussed
813   previously in Section 3.4. Furthermore, a principle of vadose zone hydrology is that water
814   percolates essentially vertically through the fracture system, but may be diverted laterally at
815   hydrostratigraphic contacts, perched water bodies, and notably around the emplacement drifts,
816   reducing the amount of water that drips into underground openings [Philip, 1990]. Moreover, a
817   shadow zone develops beneath the emplacement drift, suppressing diffusive and advective
818   releases of radionuclides into the near field [Houseworth et al., 2003]. These beneficial effects are
819   a direct result of capillary forces, which only occur in unsaturated rocks, i.e., they are not active
820   in a saturated zone repository. However, predicting the capillary barrier effect is complex,
821   because flow diversion depends on two-phase parameters that are difficult to determine for
822   fractured porous media [Finsterle, 2000; Finsterle et al., 2003]. Moreover, the amount and
823   distribution of dripping depends on the difficult to characterize small-scale roughness of the
824   drift ceiling, which can drastically change after partial drift collapse. Condensation further
825   complicates the prediction of the in-drift environment, specifically during the thermal period.
826   As a consequence, titanium drip shields had to be added to the engineered barrier system to
827   prevent water from dripping directly onto waste packages, and—as a side benefit—to prevent
828   mechanical damage due to rock fall. In summary, the unsaturated zone may be a viable location
829   for a nuclear-waste repository, offering certain benefits. However, it has considerable
830   drawbacks, such as the oxidizing environment and the fact that the vertical downward flow of

831   contaminated water will eventually encounter a near-surface aquifer. Most importantly,
832   unsaturated conditions make the system exceedingly complicated to characterize, analyze,
833   understand, predict and, therefore, defend in a license application; no credit could be taken for
834   many of the benefits mentioned above.

835 • *Thermal Regime* — In the unsaturated zone of Yucca Mountain is near atmospheric pressure
836   conditions, where water boils at a temperature of approximately 96 °C (the boiling temperature
837   may be higher in small rock pores, or if a deliquescent brine forms). Evaporation and boiling
838   changes the geochemistry of the near field, with complex impacts on mineralization, adsorption
839   properties, and corrosiveness of the waters entering the waste emplacement drifts. It also
840   generates a pressure buildup that induces vapor flow and condensation, which are effective
841   moisture and heat transfer mechanisms. Such coupled thermal-hydrological- geochemical
842   processes have been studied for repository conditions during the thermal period, both
843   experimentally and numerically [Spycher et al. 2003; Sonnenthal et al., 2005, Mukhophadyay et
844   al., 2006]. Such analyses are very complicated, specifically because of to the two-phase conditions
845   induced by boiling, which make the resulting predictions of repository performance uncertain.
846   By contrast, the hydrostatic pressure in a deep drillhole repository prevents boiling, even under
847   highly elevated temperatures, reducing the impact of spatial variability as well as conceptual
848   and parametric uncertainties on model predictions.

849 • *Repository Site* — It is far beyond the scope of this paper to comprehensively describe and evalu-
850   ate the site-specific aspects of the Yucca Mountain repository. A summary of the natural barrier
851   system and a brief history of the extensive program needed to characterize the site can be found
852   in Rechard et al. [2014a]. Much of the effort needed is a result of the complexity of (1) its location
853   in the unsaturated zone near the land surface and above the water table, (2) the geological
854   environment indicating recent seismicity and volcanism, (3) the intricate stratigraphy, consisting
855   of sequences of porous and highly fractured tuffs, some containing lithophysal cavities,
856   intersected by faults, associated with a saturated alluvial formation extending to the compliance
857   boundary, and (4) the engineered barriers and repository concept itself, which had to be adapted
858   to reduce the impact of uncertainties in the expected system behavior. Building a repository in
859   such an environment led to a large number of features, events, and processes that needed to be
860   considered [Rechard et al., 2014b]. Moreover, addressing the complexity of the coupled
861   processes induced by the heat-generating waste required an extensive research program.

862   It is expected that a deep horizontal drillhole repository is fundamentally simpler to design,
863 construct, and operate. Most importantly, the reduced complexity of a drillhole repository will likely
864 make it easier to demonstrate its immediate and long-term safety. Finally, the modularity of the
865 drillhole concept and the relatively small size of an individual disposal project provide the flexibility
866 to abandon a site should the local conditions turn out to be unsuitable or require costly adaptations.

867   A comparison of salient features of the Yucca Mountain repository and those for the deep
868 horizontal drillhole concept is shown in Table 3. The Yucca Mountain project was suspended in 2010
869 after about $15 billion was spent; according to the U.S. Department of Energy, completion would cost
870 over $96 billion (in 2007 dollars) [DOE, 2008].

871   **Table 3.** Comparison between Yucca Mountain repository and the proposed deep horizontal
872   drillhole repository.

Feature	Yucca Mountain	Horizontal Drillhole Repository
depth	0.3 km	>1 km
aquifer	below disposal section	above disposal section
geologic setting	volcanic	igneous/metamorphic/sedimentary
hydrogeologic setting	unsaturated/oxidizing	saturated/reducing
repository concept	centralized	regional/modular
transportation	inter-state	none or local
length of tunnels/drillholes to dispose 63,000 tons of SNF	50 km	1,320 km
diameter of disposal hole	6 m	0.45 m
excavated volume	1,400,000 m^3	200,000 m^3
backfill	no	yes
boiling point of water at depth	100 °C	>300 °C

873   *4.2. Deep Vertical Borehole Disposal*

874   The approach described in this paper was inspired by the DOE deep borehole disposal program;
875   however, it differs in several important aspects. The DOE program considered vertical holes drilled
876   3 miles (5 km) deep into crystalline basement rock, typically granite, which underlies sedimentary
877   formations. The waste was to be disposed in the bottom 1 to 2 kilometers of the borehole [Brady et
878   al., 2009; Freeze et al., 2013]. In contrast, the horizontal drillhole method emplaces waste canisters in
879   the horizontal section of a drillhole, deeper than for mined repositories, but not as deep as needed
880   for vertical boreholes.
881   Most of the differences between these two concepts are a direct result of the different orientation
882   of the disposal section:
883   • *Stratigraphy* — The subsurface is predominantly stratified horizontally. (Note that such horizon-
884   tal stratification is less pronounced in the more monolithic crystalline basement, which is the
885   target host rock of DOE's deep borehole proposal). Similarly, most relevant conditions (specifi-
886   cally total stress, lithostatic and hydrostatic pressures, temperature, and fluid density) are also
887   stratified horizontally. This means that a vertical borehole is likely to traverse many discrete
888   hydrostratigraphic interfaces and encounters constantly varying conditions. By contrast, the
889   horizontal drillhole can be aligned in the principal dimension of the formation and encounter
890   similar thermodynamic conditions and state variables along its length. A notable exception is
891   the probability of intersecting steeply dipping faults, which is higher for a horizontal than a
892   vertical borehole. While deep basement rocks can be thick, the vertical length of the disposal
893   section is restricted by depth limitations, whereas relatively long horizontal disposal sections
894   can be drilled.
895   • *Vertical Gradients* — The fact that pressure, temperature and salinity are relatively uniform in a
896   horizontal drillhole implies that gradients inducing fluid flow and radionuclide transport are
897   relatively small. In a vertical drillhole, decay heat from the high-level waste (superimposed on
898   the natural geothermal gradient) induces thermal convection cells that are aligned with the
899   orientation of the borehole [Marsic et al., 2006], which may be regarded as a preferential flow
900   path that passes through the horizontal, confining layers of the natural barrier system. By
901   contrast, the density differences created by thermal expansion do not induce significant
902   buoyancy-driven flow in a horizontal drillhole. Note that the vertical salinity increase and
903   associated density stratification is beneficial in both the deep vertical disposal concept and the
904   vertical access section of the horizontal drillhole repository. In the former, however, the
905   stratification is disturbed during the thermal period and needs to be reestablished afterwards—

906   a process that also leads to fluid flow. While minor, such gradients and associated flows should
907   be mitigated, as is the case in the horizontal drillhole concept. Finally, the natural geothermal
908   gradient leads to non-uniform and considerably higher ambient temperatures in the disposal
909   section of a vertical borehole repository, with several implications on overall performance.

910   •   *Mechanical Load* — The stacking of heavy waste packages in the vertical disposal borehole leads
911   to a considerable accumulated load on the canisters. Detailed stress analyses [SNL, 2016] indicate
912   that safety factors are relatively small, specifically for deep canisters that experience high loads
913   and reduced axial and radial crush resistance because of reduced yield strength at high
914   temperatures. As a precaution, multiple bridge plugs need to be installed to bear the weight of
915   additional waste packages emplaced above. Plugs, however, are considered by some as the
916   weakest link in the vertical borehole approach [Sapiie and Driscoll, 2009]. Similar issues need to
917   be addressed for the casing and compaction of backfill materials. None of these technical
918   complications apply to canisters arranged horizontally, leading to a simplified performance
919   assessment calculation with fewer scenarios. Moreover, a lighter design can be chosen for the
920   canisters and casing, with added benefits regarding handling, emplacement, retrievability,
921   effects from corrosion products, and cost. Finally, the length of the disposal section is not limited
922   by the accumulation of stacking loads.

923   •   *Drilling and Waste Emplacement* — The drilling technology developed by the oil, gas and geother-
924   mal industries is sufficiently advanced to allow for deep vertical or directional drilling in
925   different geological settings. Drilling costs depend mostly on depth, diameter, casing design,
926   and local geologic conditions [Augustine et al., 2006]. Vertical borehole disposal may consider
927   the free-fall method for waste emplacement [Beswick et al., 2024; SNL, 2016], an option not
928   available for a horizontal drillhole repository, where a wireline tractor, coiled tubing, or drill
929   pipe is needed to push the canisters into the disposal section. Emplacement risks are discussed
930   in detail in SNL [2016].

931   Borehole disposal repositories with either vertical or horizontal waste disposal sections share
932 many advantages and challenges. Table 4 summarizes some of the differences between the two
933 concepts.

934   **Table 4.** Comparison between deep borehole disposal and the proposed deep horizontal drillhole
935   repository concept.

Feature	Vertical Borehole Disposal [1]	Horizontal Drillhole Repository
depth	3–5 km	>1 km
geologic setting	Crystalline basement rock	igneous/metamorphic/sedimentary
pressure, temperature, stress	higher	lower
conditions and properties	depth-dependent	constant
buoyancy forces	aligned with borehole	absent
stacking load	yes	no
canister	heavier	lighter
waste emplacement	easier	more difficult
disposal-section length	limited by depth and load	potentially long

936   [1] A direct comparison between the deep borehole disposal concept and the Yucca Mountain repository
937   can be found in Brady et al. [2009].

5. Summary and Concluding Remarks

The horizontal drillhole repository concept is presented here as an approach for the disposal of spent nuclear fuel and high-level nuclear waste. It builds on and complements existing repository designs. Its modular design allows it to be used to supplement other methods without the high cost of building a large facility. We consider deep horizontal drillhole disposal a viable concept mainly for the following reasons:

- Radioactive waste is effectively isolated from the accessible environment by the great depth of the repository and the thick, protective natural barrier system above it—this is the essence of geological waste disposal.
- The concept is comparatively simple. Complexity is reduced in all aspects related to building and operating the repository, including siting, construction, waste handling, transportation, emplacement, sealing, and closure. Most importantly, the inherent simplicity of the concept leads to a more robust and more defensible safety assessment, with markedly fewer, less intricate features, events, and processes that need to be examined.
- The repository has a compact geometry, but a locally lower waste density. The small diameter of the disposal drillhole reduces the size of engineered barrier components, simplifying their construction and, consequently, increasing their robustness. The cross-sectional area available for fluid flow and radionuclide transport along the drillhole and excavation disturbed zone is substantially smaller than in a mined repository. The relatively low waste density in the linear drillhole arrangement distributes heat production, decreases the criticality risk, and the consequences associated with disruptive events.
- The concept offers great flexibility, both globally and locally. Drillhole repositories of different sizes can be built in a modular fashion, tailored to the specifics of the waste inventory as well as geographical and geological conditions. In particular, relatively small repositories can be built on the sites where the waste is produced, limiting or avoiding transportation. Locally, the design of the repository can be adapted to the geologic conditions (and other constraints) by changing the number, length, orientation, and inclination of the disposal sections. This global and local flexibility allows for a staged approach, with short implementation times and immediate site closure after waste emplacement, reducing overall risks and costs.
- The simplicity, compactness and flexibility of the drillhole disposal concept also reduce logistical complexity. Specifically, no humans need to be underground, transportation is reduced or avoided, and established drilling technology can be used. This reduces the need to build and license additional, complex infrastructure. Logistical simplicity increases operational safety and reduces costs.

The proposed concept faces the following main challenges:

- In the United States, the absence of a legal framework and uncertainties about the regulatory environment complicate the planning and preparation of a license application for a deep horizontal drillhole repository. In the U.S., the Nuclear Waste Policy Act currently does not allow a second repository for commercial spent nuclear fuel until the Yucca Mountain facility is completed; note that there is no similar restriction for the disposal of defense waste (such as the Cs/Sr capsules). No licensing protocol exists yet for a modular, deep horizontal drillhole repository. While multiple, individual license applications need to be prepared, it is conceivable that these applications would be simpler than that for a large mined repository (due to the relative simplicity of the drillhole concept). Moreover, the parts of the application (e.g., related to drilling and emplacement technologies), which are not related to site-specific conditions, are likely to be transferable between sites. A regulatory perspective for deep borehole disposal is provided by Winterle et al. [2011].
- Characterization by direct inspection of the host rock by humans working underground is not possible in a drillhole concept. However, as discussed in Section 4.1, we believe that the suite of advanced borehole-based coring, logging, testing, and characterization methods currently available provide sufficient information about the safety-relevant properties of the host

989　formation. Moreover, the data collected in drained, ventilated, large underground openings are
990　difficult to interpret and may not accurately reflect post-closure repository conditions. Also note
991　that a large component of site characterization (also for mined repositories) consists of surface-
992　based geophysical surveys and geological mapping. Characterization needs may be different for
993　drillhole repositories than mined repositories due to their relative simplicity and reduced
994　perturbation of the host rock by excavation and operation of large underground openings. And
995　finally, visual inspection of drillholes *can* be done with remote cameras. Videos of such
996　inspections are readily available online on YouTube; a search for "borehole camera" yields many
997　such videos. To take advantage of such a capability, the hole needs to be filled with a clear brine
998　for an inspection stage that would take place prior to the placement of the canister. Such a stage
999　is straightforward in the drilling industry.

1000　• Scientists, engineers, regulators, stakeholders, and the public need to gain confidence in the
1001　expected performance and safety of the repository. This is only possible after comprehensive
1002　performance assessment studies and a related safety case have been presented. Developing a
1003　defensible license application depends—in part—on the legal and regulatory framework, which
1004　may need to be adapted to accommodate the deep horizontal drillhole concept. Nevertheless,
1005　many aspects of the proposed concept can be based on decades of research, testing, engineering
1006　analyses, and experiences made worldwide by independent institutions, nuclear waste
1007　management organizations, as well as the oil, gas, and geothermal industries. Additional
1008　technical arguments specifically related to a drillhole repository were presented in Section 3
1009　above.

1010　In this paper, we focus the discussions on the technical aspects of this novel waste disposal
1011　concept. For the proposed technology to become a viable solution for the protection of human health
1012　and the environment from the long-term effects of spent nuclear fuel and high-level radioactive
1013　waste, the regulators and the public must accept it. Engaging these stakeholders throughout the
1014　conceptualization, development, and implementation of a waste disposal solution is not only
1015　essential, but also the main goal of the descriptions and discussions presented in this article.

1016　**6. Patents**

1017　The basic approach is patented by Deep Isolation: U.S. patent 10,002,683 B2.　Two other patents
1018　have been allowed but not yet issued (as of March 2019); several others have been applied for.

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