Accelerated High-Temperature and Pressure Demonstration of Deep Borehole Disposal Canister Technology – 25571

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ABSTRACT

This paper presents the results of the first test of deep borehole disposal (DBD) materials under high temperature and pressure conditions in an underground facility simulating the conditions of a disposal zone. The project, named **S**equential **Advan**cement of **T**echnology for DBD (SAVANT), initiated in September of 2023 under the aegis of the Deep Borehole Demonstration Center and with co-funding from Deep Isolation, the UK Government, and the US Government. The project was designed to reflect priorities of international stakeholders interested in deep borehole disposal – which, as set out in a paper presented by the Deep Borehole Demonstration Center at Waste Management Symposia 2024 [1], have identified testing of the disposal canister components as key for achieving rapid and significant benefits for the technical maturity of the overall repository system.

The full-scale, accelerated corrosion test of canister and casing coupons took place in a US based, state-of-the-art underground test cell designed for testing the endurance of oil and gas tools in extreme environments, including subsea applications. Rather than using a canister with an internal heater emplaced in a borehole (requiring ~1 year to reach target temperatures), conditions prototypic of the peak temperatures of a disposal zone were achieved by heating and pressurizing the fluid surrounding coupon samples. The target test conditions – submersion in a saline fluid at a constant pressure of 415 atmospheres (6,100 PSI), and a temperature of 193°C (380°F) – are analogous to that which the canister would experience in a fluid-filled borehole at a depth of 4 km or ~2.5 miles. The temperature is prototypic of the peak temperature of a DBD canister housing a high-powered (~1.5 kW) PWR spent fuel assembly, experienced 60 years after disposal. This temperature also approaches the limit of typical oil and gas tools (~200°C). The test cell reached its design conditions on August 13th and held them until September 12th, at which point the coupons were removed from the test cell and analyzed to calculate the corrosion performance.

The test assembly included a coupon tree that was subjected to this simulated deep borehole environment for over 30 days. The coupon tree, comprised of samples of carbon steel, duplex stainless steel, and galvanic couples of the aforementioned materials, each had precisely measured weights and dimensions to enable the corrosion rate to be calculated from the mass loss of the coupon. Prior laboratory testing of this material in March of 2024 at atmospheric pressure and near-boiling temperature indicated no measurable corrosion on duplex stainless steel over that period. The data generated from this test improves confidence in the corrosion behavior of both the canister and equipment associated with deep borehole disposal, supporting the design objectives for short-term retrievability of nuclear waste canisters from deep boreholes.

INTRODUCTION

To expand options and provide more modular and safe architectures to address the global need for geologic disposal of nuclear waste, there have been many calls to develop and test the concept of deep borehole disposal (DBD) [2], [3], [4], [5] in the last 10 years, and both Deep Isolation and the Deep Borehole Demonstration Center (DBDC) have sought to answer these calls. With the vertical concept [6], a vertical borehole is drilled to a depth of 3 km[1] and canisters are loaded into the deepest 1.5 km of the borehole. In the horizontal configuration of DBD, holes are initially drilled vertically and then gradually turned horizontal to create a disposal section that extends for ~1 to 1.5 km along a suitable, stable, low permeability host rock formation, such as shale. During the construction of the borehole, a steel casing is inserted along the length of the drillhole and the annulus between the casing and the surface of the drillhole is filled with cement. The steel (e.g., L80-1) casing aids in canister emplacement, provides structural support, and separates the fluid environments inside and outside of the casing until it corrodes and eventually prevents retrieval of canisters from the borehole. Canisters made of corrosion-resistant alloys (CRA) containing the waste are emplaced within the disposal section.

Prior to emplacement, the borehole is filled with fluid of controlled composition to reduce corrosion and to provide support against the compressive lithostatic forces experienced by the casing and cement. In Deep Isolation's reference designs [6], [8], [9], between 150 – 250 canisters can be emplaced in each borehole. Once filled, the borehole is sealed with clays, cements, and other appropriately selected sealing materials [10]. While the cement and casing theoretically provide some barrier and/or retardant to radionuclide release and migration, the metal canister is the primary non-permeable barrier relied upon following canister emplacement in Deep Isolation's DBD performance assessments. Thus, the combination of the canister and waste form could provide multibarrier and engineered containment functions in the disposal zone. Sensitivity studies completed by Deep Isolation show that even when instant canister failure and the resultant release from the waste are assumed [6], [9], peak doses do not change significantly, and the long-term performance goals are still met by several orders of magnitude. As a result, these simulations suggest that the canister's function (in the context of disposal) will be primarily to ensure the safe emplacement (and potential retrieval) of the waste to and from the disposal zone. Thus, the lifetime targets are expected to be relatively short (e.g., 50 years) compared to those for mined repository waste packages. Despite the reduced lifetime targets for the canister, corrosion testing is needed to validate these assumptions.

Deep Isolation's reference design for DBD canisters [11] contain individual pressurized water reactor (PWR) spent fuel assemblies. With funding from the U.S. Department of Energy's (DOE) Advanced Research Projects Agency – Energy (ARPA-E), Deep Isolation is commercializing a Universal Canister System (UCS) which will expand the applicability of storage, transportation, and disposal canisters to encompass waste streams from advanced reactors and fuel cycles, including vitrified waste, TRISO spent fuel, and intact halide salts from molten salt reactors. The **S**equential **Advan**cemen**t** of DBD (SAVANT) project was subsequently proposed to and funded by ARPA-E in 2023 to experimentally test the components of DBD materials under prototypic temperatures and pressures through 2025. This paper summarizes the results of the first year of corrosion testing completed in the SAVANT project and identifies future work necessary to advance DBD technologies either through Deep Isolation and/or the DBDC.

[1] Vertical boreholes have been considered for depths exceeding 3 km [7], but Deep Isolation does not currently extend its design and analyses beyond these depths.

DISCUSSION

Corrosion and canister integrity generally play a larger role in the long-term safety case of mined repositories which are subject to near-surface flows that can more rapidly transport fluids from the disposal zone to the surface, compared to DBD. For example, the canister designed by SKB International utilizes a copper shell (structurally reinforced by cast iron) that was assessed to provide a safety function and containment of radionuclides for a period of >100,000 years [12]. In Finland, Posiva's geologic repository includes a similar copper shell for corrosion resistance. The container design, corrosion modeling, and performance of various national nuclear waste disposal programs have been recently evaluated, though such evaluations seldom consider canisters compatible with deep borehole disposal [13].

Prototypic DBD Conditions and Materials

Due to its geometry, DBD disposal zone temperature will peak relatively early and within the first 10 to 100 years of emplacement of waste [14], [15] with the maximum temperature depending on the decay heat of the emplaced waste. With Deep Isolation's early analyses of 30-year aged SNF (typically PWR) assemblies disposed at a depth of 1 km, the projected temperatures reached close to 100°C. At greater disposal depths (up to 3 km) and with fuel (from advanced or conventional reactors) with a shorter cooling period and higher heat load at emplacement (e.g., 2 kW), temperatures could reach 200°C in the first 100 years, according to preliminary analyses completed as part of the UCS design project.

Generally, pore fluids at DBD disposal depths of 3 km are expected to be highly saline, reaching concentrations up to 200 g/L [16] and producing hydrostatic pressures of 32.6 MPa (4,700 PSI). As a result of the elevated hydrostatic pressure (compared to a mined repository which is loaded at near atmospheric pressure), temperatures well above 100°C may be experienced – and tolerated without boiling – in a DBD repository. Particularly when drilling in shale, the borehole would be filled with drilling fluids that match the high salinity of the surrounding host rock to avoid undesirable swelling or shrinking of the host rock [17]. For the purposes of these tests, it was assumed that the emplacement fluid (which would be emplaced through a process of flushing out the drilling fluid) would be able to lower the salinity to 1% concentration in the drilling fluid. For the purposes of designing the initial corrosion tests for SAVANT, it is conservatively assumed that there are no corrosion inhibitors in the emplacement fluid.

The material of construction for the canister is a standard class duplex stainless steel grade 2205. Duplex stainless steels obtain their corrosion resistance from high chromium concentrations (>20% in solid solution), are named for a near 50/50 austenite/ferrite phase balance, and are particularly resistant to pitting and attacks from chlorides and some acidic environments. The casing material is assumed to be American Petroleum Institute (API) 5CT[2] L80-1, a ferritic material, and the longevity of the casing is expected to be less than that of the canister due to the thickness of the casing being ~1/2 canister thickness, the corrosive effects of the environment, and the given service conditions. The conditions and materials are compared against other geologic disposal designs in Table 1.

[2] CT: Casing and Tubing.

Table 1. Overview of various geologic disposal conditions and canister materials [13], with comparison to DBD.

Country	Host rock	Max. container temperature (°C)	Chloride [Cl^-] concentration (g/L)	Container material
Belgium	Boom clay	<100	0.027	Carbon steel
Canada	Granite	100	34.3	Copper
Finland	Granite	<100	16	Copper, cast iron structural support
France	Clay	<100	2	Carbon steel
Sweden	Granite	<100	6.9	Copper, cast iron structural support
USA	Tuff (unsaturated)	200-220	0.007	Alloy 22, Ti-7 drip shield
	DBD in shale or crystalline rock	100-200	1.21*	Duplex 2205 (canister) L80 steel (casing)

*Cl^- concentration of the assumed emplacement fluid, and which corresponds to a 2 g/L sodium chloride (NaCl) concentration.

RESULTS

Laboratory Corrosion Test

For the initial phase of SAVANT, a 30-day laboratory (atmospheric pressure) corrosion test of coupons representing the casing and canister was executed using Society of Automotive Engineers (SAE) 4140 steel (deemed equivalent to the L80-1 steel for the purposes of corrosion testing) and 2205 duplex stainless steel samples. These samples were tested in uncoupled and coupled conditions to determine the effect of galvanic corrosion in a 2 g/L NaCl solution at atmospheric boiling temperatures.

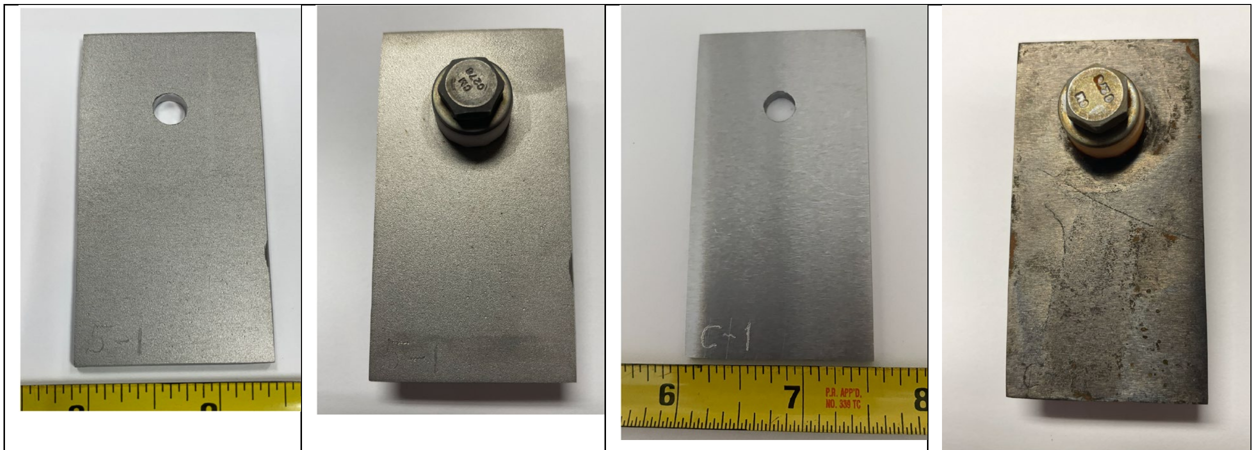
Corrosion tests were conducted by TMR Stainless in a 2 g/L NaCl solution at atmospheric boiling temperature in 1,000 mL Pyrex Erlenmeyer flasks with a cold finger condenser to prevent evaporation of the test solution. The test samples were flat rolled with dimensions of approximately 1.5” x 3” x 0.125” thick. The 2205 duplex stainless steel samples were in an annealed and pickled condition from the mill. All 2205 and 4140 samples (surfaces and edges) were polished to at least a 120-grit finish in accordance with general test specimen guidance from the American Society for Testing and Materials (ASTM) Standard G48. and the 4140 samples were polished to a 240-grit finish prior to testing.

The Galvanic coupling of 4140/2205 flat rolled samples was conducted using C276 nickel alloy fasteners and Teflon washers to isolate the C276 from the 4140/2205 coupling. A 1:1 area ratio was used on the 4140/2205 coupled samples. The uncoupled 4140 and 2205 corrosion test specimens were also assembled using C276 hardware, and PTFE[3] tape and washers were used to isolate the C276 bolts from the specimens. The C276 hardware was tightened to a torque of 14 in-lbs per ASTM G48 – Method F procedure for all the samples used in this project.

The three test samples (one of each material and one galvanic couple) were measured, weighed, and photographed before and after exposure testing to characterize the surface conditions and quantify the corrosion rate. The 2205 stainless steel samples did not exhibit measurable or significant weight loss during the 30-day exposure period and were completely resistant to the boiling 2 g/L saline solution. The

[3] PTFE: Polytetrafluoroethylene, also known as Teflon.

4140-steel sample exhibited a general corrosion rate of 6.1 mils per year, and when the 4140 steel was coupled to the 2205 stainless steel the galvanic corrosion rate was 9.1 mils per year. The maximum depth of pitting corrosion on the two carbon samples was similar, but the diameter of the corrosion pits was significantly larger for the galvanically coupled C-2 sample. Photos of the coupons before and after testing are shown in Figure 1 and Figure 2 below.



(a)	(b)	(c)	(d)

Figure 1. Before and after photos of the coupons of the canister (a/b) and casing (c/d) materials.

(a)	(b)	(c)	(d)

Figure 2. Before and after photos of the galvanically coupled coupons of the canister (a/b) and casing (c/d) materials, tested in boiling temperatures for a 30-day period.

While the temperature and pressure conditions of this test were not as high as in the later field test or even the desired disposal environment, it is worth noting that this laboratory test occurred in a fully oxidizing environment, which would be expected to promote much more aggressive corrosion relative to anoxic conditions found at deep borehole disposal pressures or depths.

High Temperature and Pressure Underground Corrosion Test

The designed test conditions for the 30-day high temperature and pressure test are summarized in Table 2 below. The test duration, conditions, and data acquisition of the extent achieved were only possible through the joining of UK Energy Entrepreneurs Fund (EEF) and United States (US) ARPA-E project funds, as well as the unique capabilities provided by the facility contracted to execute this test program.

Table 2: Design Testing Conditions for High-Temperature and Pressure Underground Test.

Parameter	Target	Range	Comments
Temperature	375°F (191°C)	+10°F (5.56°C)	Based on preliminary simulations of the UCS, these bounding temperatures are consistent with what would be experienced by a 2 kW UCS package near peak temperature (achieved after 60 to 100 years [18]).
		-10°F (5.56°C)	
Pressure	6100 PSI (42 MPa)	+150 PSI (1.03 MPa)	These pressures would be experienced by a canister subjected to anomalously high pore fluid pressures (corresponding to hydrostatic pressure at a depth of ~4 km).
		-50 PSI (0.347 MPa)	
Fluid Salinity	0.0167 ppg (2 g/L)	+2%	Makeup water to the system includes dissolved salts to maintain the as-loaded emplacement fluid concentration (2 g/L)
		-2%	

Pressure and temperature were continuously monitored and controlled by heaters and an automatic system. Additionally, test parameters were manually checked and recorded on an hourly basis during working hours throughout the test duration. Contingency was built in to allow for lost time due to unplanned power outages, ensuring that the test would last at least 30 days in duration under desired conditions. As a final precaution, a relief valve was programmed to relieve pressure if the system pressure rose to 46.2 MPa (6,700 psi).

After a 32-day period of testing, coupons were removed from the test cell and sent back to the laboratory (Pacific Sensor) which had initially produced them for post-test weighing and measuring, according to the ASTM G1 test procedure. A total of five 1018 carbon steel coupons (representing the casing), five 2205 duplex stainless steel coupons (representing the canister), and two galvanic pairs of these materials (representing canister/casing contact) were tested and examined. The maximum corrosion rates measured from the test are summarized in Table 3 below.

Table 3: Summary of maximum measured corrosion rates from the high temperature and pressure corrosion test, as measured by Pacific Sensor.

Material	MPY (milli-inch / year)	Micrometer / year
Carbon Steel	0.188	4.744
2205 Duplex	0.02	0.505

Notably, the carbon steel coupons corroded at a rate that was more than 10x slower compared to the laboratory experiment under the lower temperature conditions. This suggests that the oxygen free environment of the test cell (which would also exist in a deep borehole repository) has a major impact on reducing the corrosion rate of the system. Figure 3 shows the condition of the front and back of the coupons after cleaning and weighing.

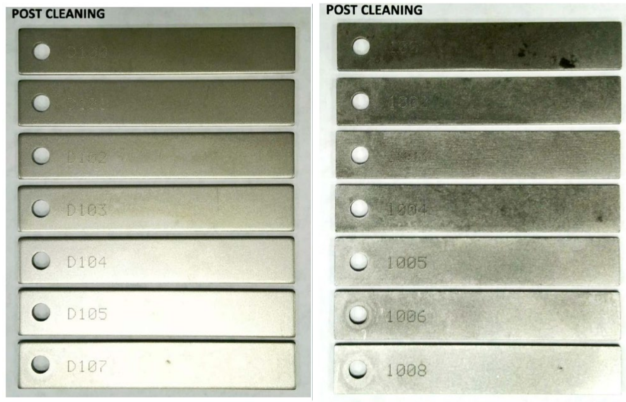


Figure 3. Photos of the coupons of canister (left) and casing (right) materials after cleaning and corrosion rate measurement.

Application of Results

The highest measured corrosion rates from these results fall well below the assumed conservative corrosion rates in Deep Isolation's working corrosion model. Based on data collected by Nagra [19] and applying margin, Deep Isolation previously assumed canister and casing corrosion rates in the disposal environment of 0.056 and 0.280 MPY, respectively. By comparison, the highest corrosion rates from this test program would suggest respective rates of 0.020 and 0.188 MPY. These rates inform the time to "failure", assumed to occur when a component is corroded to half its initial thickness[4]. Time to such failure conditions for different corrosion rates can be seen in Table 4 below[5].

Table 4: Time to Failure (Years) for Different Corrosion Rates.

Component	Nominal	New Data	New Data, All Carbon Steel
Lift Adapter	2,098	5,827	623
Canister Shell	8,926	24,795	2,653
Casing	632	1018	564

Extrapolation of these rates inherently produces a high level of conservatism, since these very high-temperature conditions will only persist over a 10 – 100 year period (due to decay heat term reduction). Application of these rates suggest likely compliance with all relevant regulations and guidance, including the most stringent international retrievability requirements (on the order of 100 years) [20], which is practically limited by the time to failure for the lift adapter and potentially the casing. Similarly, these results provide confidence in containment and confinement requirements for a canister to last at least 300 years as stipulated in 10 Code of Federal Regulations Part 60 [21] and International Atomic Energy Agency Specific Safety Requirements-5 guidance, which also alludes to an upper bound for a waste container maintaining containment over a "thermal period", potentially spanning thousands of years [22]. The exact duration of the thermal period may vary with the proposed barrier system and inventory, but these results provide initial assurances toward compliance. These findings hold true, even if the canister were also made of carbon steel, as shown in the final column of Table 4.

[4] Note that the outer diameter of casing may not be subjected to the same fluid environment and is thus assumed to corrode at the slower rate of duplex stainless steel.
[5] The assumed failure thickness may change to be less than or greater than the current 50% assumption as future work leads to model refinement.

CONCLUSION

This paper summarizes the initial test results from the first year of the SAVANT project, taking place from September 2023 to September 2024. An initial review of the corrosion mechanisms and rates in a DBD system concluded that the most effective way to determine the expected corrosion rates would be to perform corrosion testing in a metallurgical laboratory using the same materials, emplacement fluid chemistry, and conditions (e.g., chloride content, pH, temperature, etc.) expected in service. The results of the laboratory and underground testing validated the importance of recreating prototypic disposal zone conditions in terms of experimentally measuring and projecting the corrosion rates of the system. For example, the carbon steel corrosion rate was significantly (>10x) lower in the underground, high pressure, and relatively low oxygen environment, despite the fact that the temperatures were much higher (191°C vs. ~100°C).

High temperature, high pressure testing suggests that UCS canisters surpass regulatory requirements for retrievability as well as containment and confinement. Further study may be warranted to better quantify other corrosion phenomena and any compounding effects they might introduce. Additional studies across a range of temperatures and pressures would enable a more comprehensive understanding of how corrosion varies across borehole (and mined) repository conditions. Application of these findings, be they from Deep Isolation, the DBDC, and/or other entities, can better inform the technical and regulatory case for the UCS as well as quantify design margins to enable manufacturing and economic optimizations for UCS canisters and disposal solutions more broadly.

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