The corrosion of radioactive waste disposal canisters based on in situ tests

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10.1 Introduction

The safe permanent disposal of high-level waste (HLW) and spent fuel (SF) requires the development of long-lived canisters, supported by robust lifetime predictions in the overall safety assessment. Corrosion is the main time-dependent degradation mechanism leading to canister failure. Lifetime prediction models are generally based on information from a combination of laboratory experiments, in situ testing, and (for some materials) natural and archaeological analogs.

In situ tests refer to experiments conducted in an underground research laboratory (URL) that simulates, as closely as possible, the actual conditions in a deep geological repository. Experiments may be conducted at full-scale to demonstrate the behavior of the proposed system or, where the scale of the experiment is not important to the aim of the test, at partial scale in a borehole or by making use of some other aspect unique to the URL environment. In both cases, however, in situ testing takes advantage of one or more thermal, hydraulic, chemical, of microbiological aspects of the underground environment that are otherwise difficult to simulate.

The range of in situ tests conducted in URLs reflects the multidisciplinary nature of the study of the disposal of HLW/SF. In some cases testing underground at full scale is absolutely necessary, for example, for studying the consumption of oxygen trapped initially in the pores of the buffer and backfill materials [1,2]. For the corrosion behavior of the HLW/SF canister, however, in situ testing represents just one of a number of different approaches that are used for investigating and predicting the long-term behavior. For corrosion studies, in situ testing can be used to provide data for input into, or for validation of, lifetime prediction models, as well as to support the underlying mechanisms involved. Because of the planning and effort required to perform testing underground, in situ tests are typically conducted for extended durations and, hence, can provide long-term corrosion rates to support the safety assessment in situations where lifetime assessments are based on the basis of a measured or predicted corrosion rate. Being able to investigate the interaction between the canister and one or more of the other barriers, including the host rock,

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is a unique capability of in situ testing. Furthermore, evidence from tests performed under realistic disposal conditions is important for building confidence in long-term predictions of the behavior of the entire disposal system, including corrosion of the canister.

The corrosion behavior of the canister will evolve with time as the repository environment itself evolves. Warm, aerobic, and unsaturated conditions will prevail immediately after repository closure, with the environment becoming cool and anoxic as the waste decays, as the initially trapped oxygen is consumed, and as the buffer and backfill materials saturate with anoxic groundwater. This evolution will proceed on different timescales, with consumption of the initially trapped oxygen possible over a matter of months [1,2], whereas the thermal transient may last several thousands of years [3]. Therefore when planning and interpreting the results of in situ tests, it is important to understand which aspect of the overall repository evolution the environmental conditions in the test represent. Typically, the larger the scale of the experiment, the more likely it is to represent the early aerobic phase as it is practically difficult to ensure anoxic conditions in a full-scale test. Anoxic conditions representative of the long-term evolution can be achieved during in situ testing on smaller subcomponents of the disposal system.

URLs and in situ testing have long been a component of various international nuclear waste management programs [4–6]. These URLs have either been developed in preexisting (nonrepository) locations (such as the Mont Terri site in Switzerland or the Asse salt mine in Germany), as purpose-built facilities [such as the Äspö Hard Rock Laboratory (HRL) in Sweden or Bure in France], or as part of a future repository site (such as ONKALO in Finland). Table 10.1 lists all of the past and current European URLs.

Here, we review the in situ corrosion tests that are relevant for European repositories and HLW/SF canister concepts: copper/cast iron in bentonite, steel without backfill, steel with bentonite, and copper coating with bentonite. The review is divided into a discussion of the corrosion of steel and cast iron (Section 10.2) and of copper (Section 10.3). Finally, we present new evidence for the evolution of redox conditions within the repository (Section 10.4).

10.2 Corrosion of steel and cast iron

10.2.1 Äspö

The MiniCan experiment has been running in the Äspö HRL in Oskarshamn, Sweden, since 2007. The experiment reflects the Swedish KBS-3 disposal concept consisting of five small-scale copper canisters each with a cast iron insert (Fig. 10.1). The canisters were set in support cages containing low-density MX-80 bentonite, compacted MX-80 bentonite, or no bentonite. More specifically, the experiment was designed to explore the consequences of a potential leak in the outer copper shell, for example, due to a weld defect, allowing the ingress of porewater into the gap between the shell and the insert. In addition to the shell and

Table 10.1 Summary of past and current underground research laboratories in Europe (based on the compilations by refs. [4–6]).

Facility	Host rock type (depth)	Location	Years of operation	Type of construction
High-activity disposal experimental site (HADES)	Boom clay (230 m)	Mol, Belgium	1984–present	Purpose built
Bukov Underground Research Facility	Granite (600 m)	Czech Republic	2013—under construction	Preexisting tunnels, uranium mine
Josef Regional Underground Research Center	Tuff and granodiorite (<200 m)	Czech Republic	2007	Preexisting tunnels, gold mine
Olkiluoto Research Tunnel	Granite (60–100 m)	Finland	1992–present	Purpose built at repository site
ONKALO Underground Rock Characterization Facility	Granite (500 m)	Finland	2003—under construction	Purpose built at repository site
Amelie	Bedded salt	France	1986–92	Preexisting tunnels
Fanay-Augères	Granite	France	1980–90	Preexisting tunnels, uranium mine
Tournemire	Shale sediments (250 m)	France	1990–present	Preexisting tunnels
Bure URL	Shale (indurated clay) (450–500 m)	Meuse/Haute-Marne, France	2000–present	Purpose built
Asse mine	Permian rock salt (490–950 m)	Germany	1965–97	Preexisting tunnels, salt mine
Gorleben	Salt dome (<900 m)	Germany	1985–90 and 2010	Purpose built
Konrad	Limestone (800–1300 m)	Germany	1980–present	Former iron ore mine
Morsleben	Salt dome (<525 m)	Germany	1981–98	Former salt mine, repository site
Stripa	Granite (360–410 m)	Sweden	1976–92	Preexisting tunnels, iron ore mine
Äspö HRL	Granite (200–460 m)	Sweden	1995–present	Purpose-built facility
Grimsel Test Site	Granite (450 m)	Switzerland	1984–present	Adjacent to existing road tunnel
Mont Terri	Opalinus clay (400 m)	Switzerland	1995–present	Adjacent to existing road tunnel

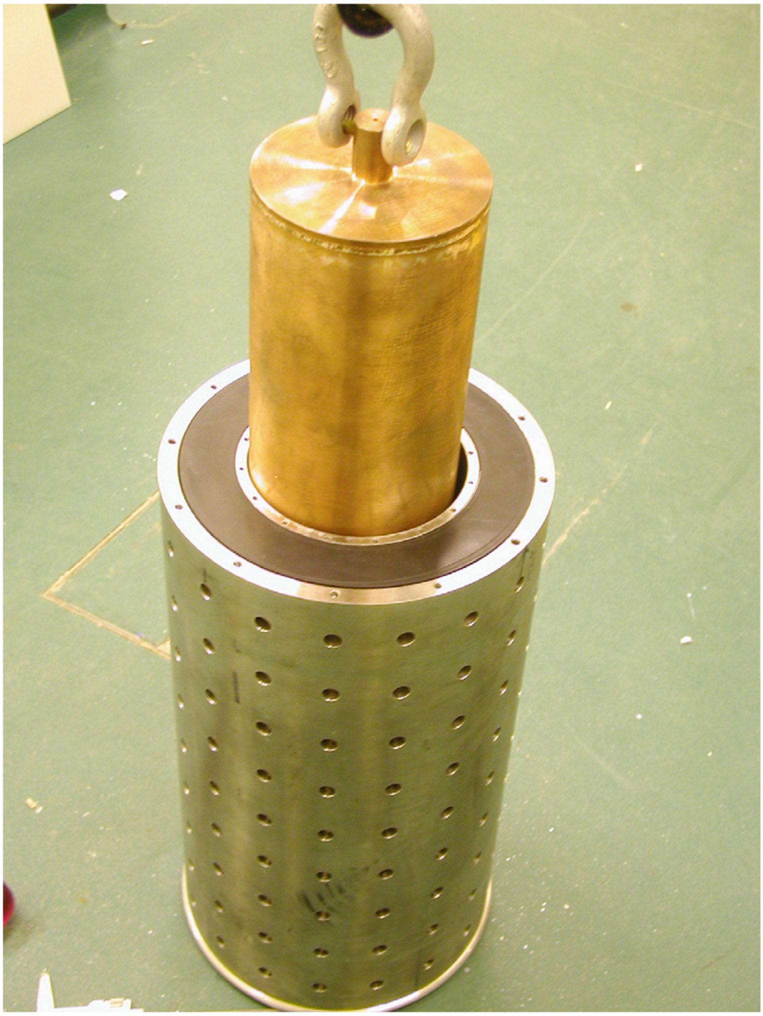

Figure 10.1 Photograph of the setup of the MiniCan experiment consisting of a copper-based canister inside a support cage with or without bentonite [7].

insert, the experiments were equipped with mass loss samples and electrodes. Online electrochemical monitoring and numerous sampling campaigns for chemical, corrosion, and microbial characterization of samples have taken place over the years. The outcome of this work has been documented in several Swedish Nuclear Fuel and Waste Management Company (SKB) reports [7–17] and publications [18,19].

The most startling results of the MiniCan experiment with the low-density bentonite was the extremely high corrosion rates exhibited by all the iron components inside the support cage containing the bentonite, even though the stainless steel support cage itself had a shiny, undamaged appearance. After 5 years, the cast iron coupons had completely corroded and X-Ray difraction (XRD) analyses indicated that the only crystalline phase was graphite. This indicates that the corrosion rate was at least 500 μm year^{-1}. The reason for the high corrosion rates was the extensive activity of sulfate-reducing bacteria (SRB) inside the support cage. The experiments with the compacted bentonite and in the absence of bentonite exhibited cast iron corrosion rates of 2.1 and 3.2 μm year^{-1}, respectively. In those cases SRB colonies were also found on the coupon surfaces.

10.2.2 Bure

The Materials Corrosion (MCO) experiment was ongoing at the Bure URL for the past several years [20]. It consisted of a vertical descending borehole allowing the anoxic exposure of carbon steel coupons (A37, SA516 grade 60, P235) in the Callovo–Oxfordian claystone either immersed in porewater or exposed to a humid atmosphere. The exposure chamber was heated to 85°C and several parameters such as pH and Eh were measured online. Detailed characterization of the coupons and gravimetric corrosion rate measurements took place after retrieval at different periods of up to 3 years, as well as microbial analyses of the porewater and of swabs from the coupons [21–23], which were linked to the evolving exposure conditions in the borehole.

An interesting outcome of this experiment was the observation of an acidic transient (as low as pH 4.5) in the porewater lasting about 200 days, which was an outcome of the oxidation of pyrite during drilling and the initial aerobic period. This acidic phase led to significant corrosion rates of up to 200 μm year^{-1} for coupons immersed in porewater. Interestingly, some other immersed coupons exhibited lower corrosion rates ($<$20 μm year^{-1}) which was explained by the presence of a siderite protective film. On the other hand, coupons exposed only to the gas phase exhibited low corrosion with rates $<$1 μm year^{-1}. Coupons that were introduced into the experiment after the end of the acidic transient were exposed to slightly alkaline conditions exhibited significantly lower corrosion rates of a few μm year^{-1}. Microbial analyses indicated the presence of various microorganisms in the porewater including SRB and thiosulfate-reducing bacteria.

As a consequence of the findings of the MCO experiment, the French disposal concept was slightly modified [24]: the annular gap (5–10 cm) between the microtunnel casing and the Callovo–Oxfordian claystone will be backfilled with a cement-bentonite mixture in order to neutralize the residual acidity.

An alternative corrosion experiment contained carbon steel and other materials in contact with Callovo–Oxfordian blocks in boreholes drilled under N_2 (to avoid pyrite oxidation and the related acidic transient) at a temperature of 50°C [25]. Corrosion rates were measured gravimetrically after retrieval revealing rates in the range of 3–5 μm year^{-1} after 2 years and 1–3 μm year^{-1} after 5.5 years. Corrosion products consisted of magnetite, siderite, and mackinawite.

10.2.3 Grimsel

Two corrosion-related experiments have been running at Grimsel: Full-scale engineered barriers experiment (FEBEX) and materials corrosion test (MaCoTe).

FEBEX was constructed according to the Spanish disposal concept and consisted of two steel heaters, simulating disposal canisters, installed horizontally inside perforated steel liners, and surrounded by highly compacted bentonite blocks. Even though FEBEX was not primarily designed as a corrosion experiment, several coupons of candidate metals (carbon steel, stainless steel, titanium, copper, and cupronickel alloys) for manufacturing disposal canisters were introduced in bentonite blocks close to the heaters. In addition, several samples from sensors, the heaters, and the liner were analyzed for corrosion. The experiment began in 1996; in 2002 the first heater was dismantled, while in 2015 the excavation of the second heater took place.

The analyses of samples from the first dismantling after 5 years of exposure [26,27] indicated that the corrosion attack depended greatly on the exposure conditions: the heater, liner, and coupons that were close to the heater exhibited only slight uniform corrosion due to the high temperature and low humidity during disposal. On the other hand, the sensors, which spanned the distance between the heater and the host rock, and were thus exposed to higher humidity, exhibited significantly more corrosion damage, including pitting, SCC, and the presence of sulfur in the corrosion products. Microbial characterization of bentonite samples housing the coupons and the sensors confirmed the complete absence of viable microorganisms close to the coupons and the heater, while both aerobic bacteria and SRBs were found close to the sensors that were further from the heater in a cooler and more humid environment. In addition, the bentonite density around the sensors was lower, since during construction the bentonite blocks were carved to fit the sensors resulting in a gap.

The analyses of coupons from the dismantling of the second heater after 18 years of exposure were similar [28]. The heater and liner exhibited only general corrosion. From the corrosion coupons, the titanium alloys exhibited no corrosion, copper-based coupons exhibited some general corrosion, while stainless steel coupons exhibited localized corrosion manifested as pitting and cracking. Again, the sensors exhibited the highest amount of corrosion damage, which was attributed to the higher humidity close to the host rock. Microbial analyses, also confirmed previous results, leading to large numbers of cultivable microorganisms from the humid, low-temperature areas, while no cultivable bacteria were found close to the heater [29]. Despite the broad agreement between the two dismantling campaigns the interpretability of the corrosion data is severely hampered by the uncertainty in the redox conditions in the experiment and the potential inflow of oxygen through the plug [30].

The MaCoTe experiment is a purpose-built corrosion experiment running since 2015. It consists of a nonheated part, which is basically identical to the IC-A experiment (see Section 10.2.4) and a heated part. Preliminary results after 1-year exposure in the nonheated part indicated slight general corrosion of carbon steel and copper coupons [31]. The corrosion characterization is supported by microbial analyses of the bentonite and porewater.

10.2.4 Mont Terri

Two corrosion experiments have been running in the Mont Terri URL over the past several years: the IC experiment [32,33], reflecting disposal conditions in France (steel in contact with the clay host rock); and the IC-A experiment [33,34] simulating disposal conditions in Switzerland (steel embedded in bentonite). Corrosion coupons have also been included in the full-scale emplacement experiment [1], but these will not be available for characterization until the dismantling of the experiment, which is expected in 10−15 years. Both corrosion experiments consist of vertically descending boreholes, sealed off by packers to ensure anoxic conditions in the test section below. However, the two experiments follow a different approach to the measurement of the corrosion rates: in the IC experiment corrosion rates are measured in situ by means of remotely controlled electrochemical impedance spectroscopy measurements, while in the IC-A experiment coupons are embedded in bentonite-containing modules (see Fig. 10.2), which are periodically extracted and analyzed by weight loss. In addition, both experiments complement the corrosion work with microbial analyses of the porewater and test coupons.

The monitoring of the corrosion rate in the IC experiment indicated initially high corrosion rates ($\sim 15\ \mu\text{m year}^{-1}$), gradually decreasing to less than $1\ \mu\text{m year}^{-1}$. It is worth noting that unclogging of the steel−clay interface by N_2 injection led to a significant increase of the corrosion rate of up to $20\ \mu\text{m year}^{-1}$ for a short period, indicating the importance of confinement and the protective effect of corrosion products. On the other hand, average corrosion rates of $\sim 2\ \mu\text{m year}^{-1}$ were reported in the IC-A experiment over an exposure period of approximately 20 months. Both experiments reported the presence of expected corrosion products including magnetite and other Fe compounds containing chlorides, carbonates, hydroxides, etc. Furthermore, active microbial populations were found in the porewater of both experiments, and both contained SRBs.

10.2.5 High-activity disposal experimental site

A long-term in situ corrosion program in Boom clay took place at the high-activity disposal experimental site URL during the 1980s and 1990s [35−37]. Different types of materials as well as waste forms were tested in different environments in numerous boreholes drilled in Boom clay. Carbon steel samples that were in direct contact with clay exhibited significant uniform corrosion damage as well as pitting (up to 240 μm deep pits after 2 years at 90°C). Average corrosion rates, measured by weight loss, of the order of $1.8\ \mu\text{m year}^{-1}$ (16°C for 4.8 years), $7.7\ \mu\text{m year}^{-1}$ (90°C for 1.8 years), and $8.6\ \mu\text{m year}^{-1}$ (170°C for 4.8 years) were reported. On the other hand, a carbon steel sample that was by mistake in contact with the stainless steel casing exhibited an average corrosion rate of $4.7\ \mu\text{m year}^{-1}$ (90°C for 7 years). Corrosion product layers had a thickness between 10 and 50 μm depending

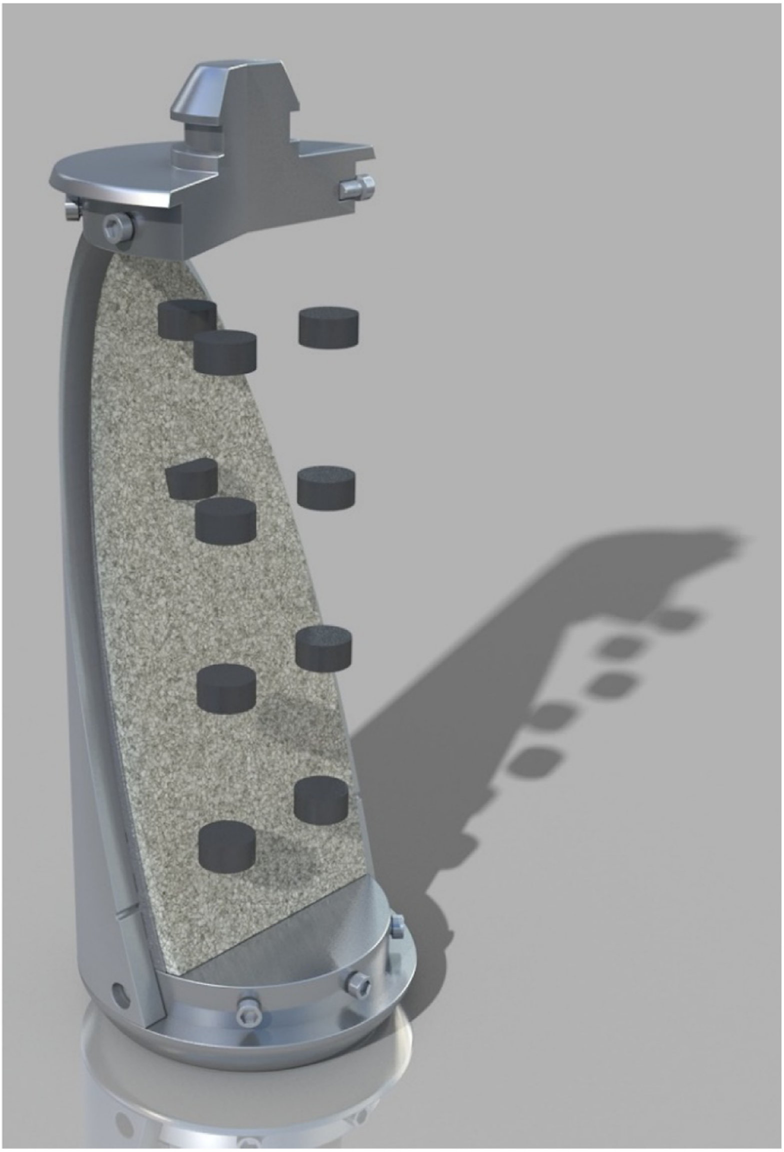

Figure 10.2 Illustration of a cutaway through a module used in the IC-A experiment containing corrosion coupons and bentonite [34].

on temperature and duration and consisted of magnetite and haematite with some incorporation of silicate originating from the clay. It was also reported that welded samples exhibited slightly deeper pits than the parent alloy.

Carbon steel also underwent corrosion when exposed to a humid clay atmosphere. Average corrosion rates after 2 years of exposure at 90°C were 9 μm year^{-1}

for as-received samples and 3.2 μm year^{-1} for polished samples. On the other hand, corrosion rates were 5.1 μm year^{-1} for as received samples and 0.4 μm year^{-1} for polished samples after an exposure of 2.5 years at 16°C. Samples that were designed with an artificial crevice exhibited identical corrosion rates to the as-received samples. Maximum pit depths also evolved with the surface state of the sample and the temperature with the shallower pits appearing in polished samples (30−75 μm), increasing to 180−195 μm for as-received samples, and 245 μm for samples with a crevice. Iron oxide with traces of chloride and sulfur was found in the corrosion products.

It is interesting to note that the conclusion of this long-term study was that carbon steel is an unsuitable candidate container material to be used in contact with Boom clay.

In another corrosion experiment (CERBERUS project), in situ measurements were done in the presence of radiation [38]. After a direct exposure to Boom clay for 8.5 years (5 years at 80°C) in a radiation field carbon steel exhibited an average corrosion rate of 3.8 μm year^{-1}, while a corrosion rate of 20.3 μm year^{-1} was reported for a welded sample. In comparison, under similar conditions but in the absence of irradiation a welded sample exhibited a corrosion rate of 4.6 μm year^{-1}. Severe pitting combined with intergranular attack was reported for the irradiated samples, with pits as deep as 150 μm.

10.3 Corrosion of copper alloys

The use and significance of data from in situ tests differ somewhat for copper compared with that described earlier for steel and cast iron. For these latter materials, it is common to use empirical measurements to predict the extent of corrosion under anoxic conditions for the safety assessment. Thus long-term corrosion rates from in situ experiments are of direct relevance for lifetime predictions. In the case of copper canisters, however, lifetime predictions are typically based on either mass-balance or mass-transport arguments, for aerobic and anoxic conditions, respectively [39]. Therefore measurements of the corrosion rate of copper samples from in situ tests are of less use than for iron-base alloys. Of more interest are observations, or not, of localized corrosion under aerobic conditions or of other features, such as copper concentration profiles in compacted bentonite [40], that provide mechanistic insight.

The majority of in situ tests carried out with copper samples have been performed by SKB at the Äspö HRL in Sweden. Data from individual tests are described in the following sections. In addition, copper samples have been included in a number of other experiments at various URLs, and these are summarized in Section 10.3.4.

10.3.1 *Long-term test of buffer material*

The long-term test of buffer material (LOT) in situ experiment consists of a series of seven vertical boreholes containing a central copper heater surrounded by rings of compacted bentonite (Fig. 10.3). Two series of tests were planned, the S series under “standard” conditions representative of a KBS-3 repository and an A series under “adverse” conditions of elevated temperature and additives to the bentonite. Four of the seven test parcels have been withdrawn to date following exposure periods of up to approximately 6 years.

Although the test was primarily aimed at the study of mineralogical changes to the clay, a number of oxygen-free phosphorus-doped copper weight-loss coupons were included in bentonite rings 22 and 30 (Fig. 10.3). Parcel A2 also included three cylindrical copper electrodes in bentonite ring 36 to enable real-time electrochemical noise monitoring [42–44]. The test parcels were assembled and installed under aerobic conditions and any resulting corrosion would reflect the initial warm, oxidizing period of the evolution of the repository environment.

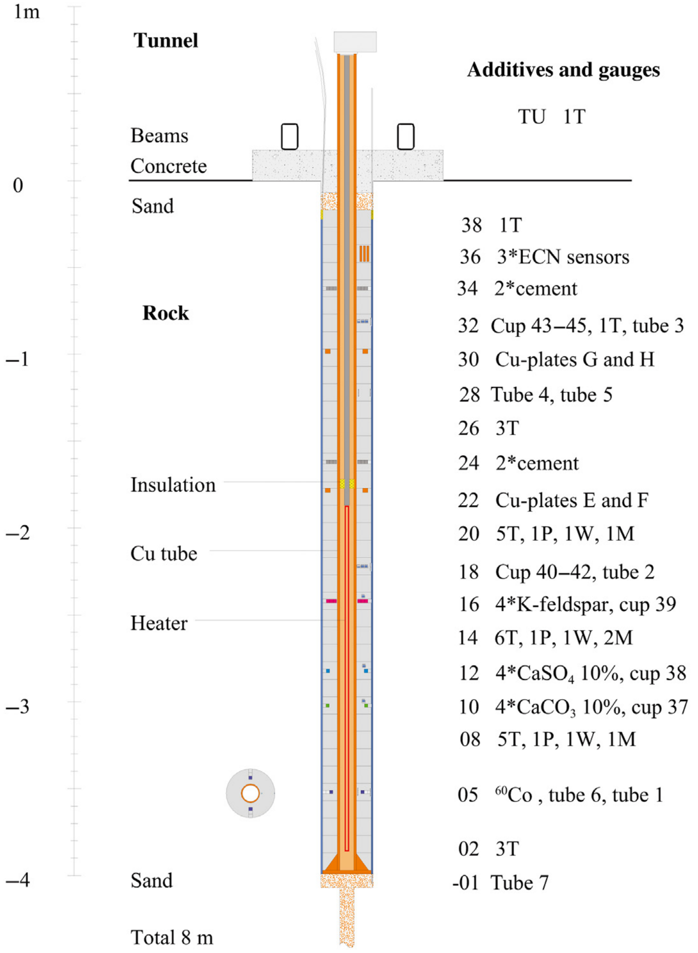

Figure 10.3 Schematic of the long-term test of buffer material (LOT) parcel A2 [41].

The primary information from the LOT tests to date is weight-loss corrosion rates. The rate is found to decrease from values of 2−3 μm year^{-1} for exposure period of 1−2 years [45,46] to 0.2−0.4 μm year^{-1} after 6 years [41]. The decrease in the corrosion rate with increasing exposure may reflect the gradual consumption of the initially trapped atmospheric oxygen or may be the result of a Cu(II)-diffusion limited process, as suggested by King et al. [47] for the corrosion of copper in aerobic compacted bentonite. Interestingly, Wersin [40] observed copper concentration profiles in the bentonite in contact with the corroding copper coupons from the LOT experiment similar to those observed in laboratory experiments and associated with the proposed transport-limited corrosion process [47].

10.3.2 Prototype repository

The prototype repository (PR) is a full-scale demonstration of the installation and performance of six copper canisters in the Äspö HRL based on the KBS-3 repository design (Fig. 10.4). The canisters are heated and the environmental conditions simulate as closely as possible those expected during the early evolution of the repository. In addition to the posttest examination of the copper canisters themselves, corrosion information is obtained from a commercial electrochemical monitoring technique used to measure the corrosion rate of test electrodes in some of the deposition holes [49,50].

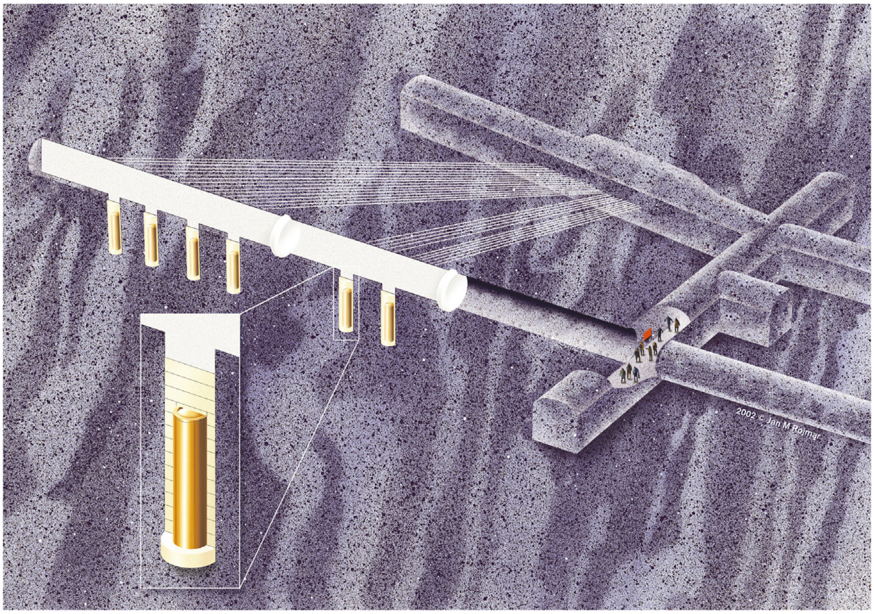

Figure 10.4 Schematic illustration of the configuration of the prototype repository in situ test comprising six full-scale canisters installed at the Äspö Hard Rock Laboratory [48].

The two canisters closest to the access tunnel were excavated after approximately 8 years of exposure. Machining profiles on the canisters were still clearly visible indicating relatively little corrosion had occurred. There were no visible indications of localized corrosion, although scanning electron microscopy (SEM) analysis indicated some pit- and crack-like surface anomalies, although these may have been present from the outset [48,51]. As would be expected following exposure to aerobic conditions, the canister surface showed indications of both cuprite Cu_2O and malachite $Cu_2(OH)_2CO_3$ corrosion products, the latter suggesting a relatively low chloride concentration in the bentonite porewater. No increase in absorbed hydrogen content was found. The electrochemical monitoring system indicated real-time corrosion rates of the order of 1 μm year^{-1}.

10.3.3 MiniCan experiment

Unlike the LOT and PR in situ tests that were primarily designed to study the behavior of the buffer and of the entire engineered barrier system, respectively, the Miniature Canister (MiniCan) experiment was specifically designed to assess the corrosion behavior of copper and cast iron under simulated disposal conditions. As described in Section 10.2.1, five of the miniature canisters shown in Fig. 10.1 were installed in near-horizontal boreholes at the Äspö HRL. At the time that the experiment was designed in 2005, the importance of highly compacted bentonite for the suppression of microbial activity was not fully appreciated, which resulted in experimental designs with either highly compacted bentonite, loosely compacted bentonite which chemically conditioned the incoming groundwater, or no bentonite at all (Fig. 10.5).

In hindsight, the selection of these different bentonite configurations was fortuitous as it highlights the importance of bentonite density in suppressing microbial activity. As described in Section 10.2.1, extensive microbial sulfate reduction occurred in MiniCan 3 and 5 with low-density bentonite [14] or no bentonite at all [17], respectively. Perhaps the most remarkable observation from MiniCan 3 was that, although the extent of sulfide formation was so great that the cast iron coupon had completely corroded away (minimum corrosion rate of 500 μm year^{-1}), the corrosion rate of a copper coupon exposed to the same environment was only 0.15 μm year^{-1} [19]. In contrast, in MiniCan 4 containing highly compacted bentonite, the corrosion rate of the copper sample was only 0.02 μm year^{-1} [17].

10.3.4 Other in situ experiments

Various types of copper coupons have been installed in other in situ tests at Äspö and at the Grimsel Test Site and Mont Terri URL in Switzerland. Samples of the Swedish reference grade of oxygen-free, phosphorus-doped OFP copper have been installed in the Alternative Buffer Material (ABM) test at Äspö [53]. Samples of wrought OFP copper and of both cold spray and electrodeposited copper have been installed in modules of the MaCoTe and IC-A experiments at Grimsel (Section 10.2.3) and Mont Terri (Section 10.2.4), respectively.

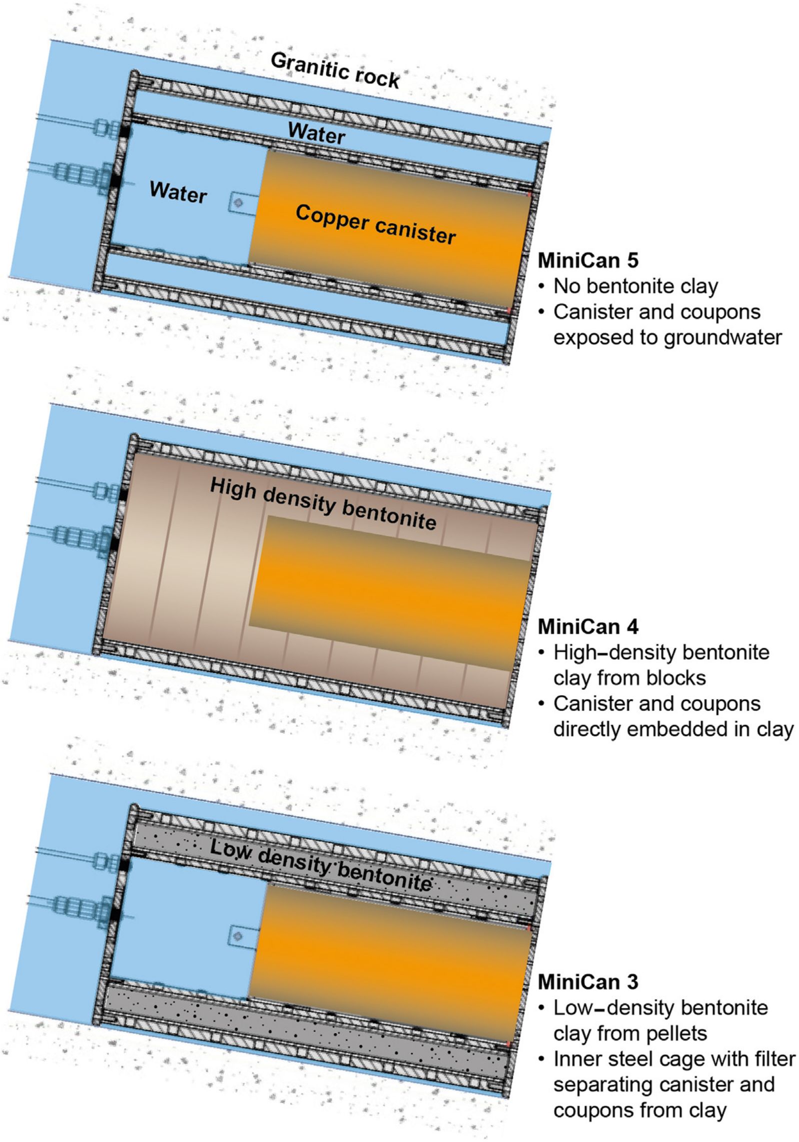

Figure 10.5 Illustration of three of five miniature canisters (MiniCan) tests installed in near-horizontal boreholes at the 450-m depth at the Äspö Hard Rock Laboratory [52].

10.4 Evolution of redox conditions

Understanding the evolution of the redox conditions within the repository, and in particular the duration of the initial aerobic phase, is of crucial importance for predicting the corrosion behavior of the canister. The FE-G experiment at Mont Terri

(Section 10.2.4) has given indications of very rapid O_2 consumption in a full-scale simulation of the in-room disposal method proposed by Nagra [1]. The experiment comprises three steel heaters in a 50-m-long tunnel that was backfilled with granular bentonite (Fig. 10.6).

Oxygen sensors located at different positions along the length of the tunnel were used to measure the concentration of residual atmospheric O_2. The oxygen concentration was found to decrease within a matter of weeks following backfilling of the different sections of the tunnel (Fig. 10.7). More importantly, the O_2 was consumed at a time when the relative humidity at the surface of the steel heaters simulating the HLW/SF canisters would have been too low to sustain aqueous corrosion processes. Other processes that may have consumed the O_2 include corrosion of the steel mesh and tunnel supports, microbial activity in the wetter regions of the buffer

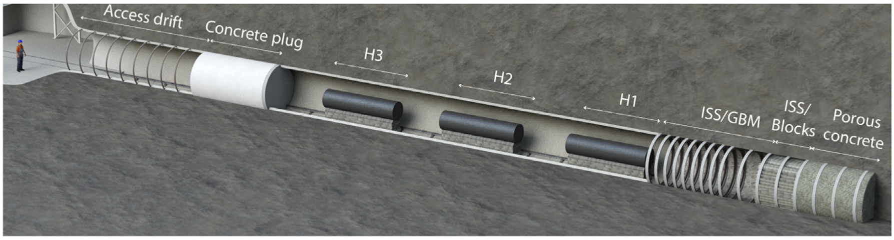

Figure 10.6 Schematic of the FE-G experiment at Mont Terri showing the relative location of the three heaters and sealing materials [2].

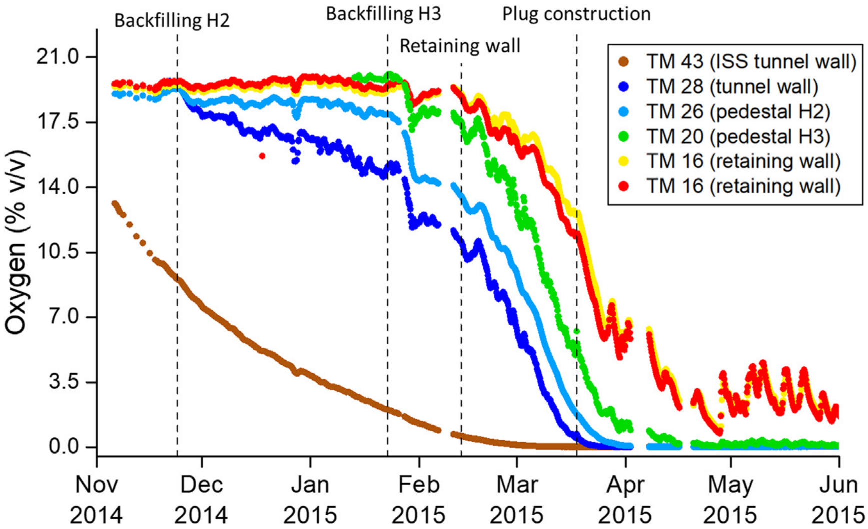

Figure 10.7 Time dependence of the residual oxygen concentration based on readings from six sensors at different locations in the FE-G tunnel as the experiment was progressively backfilled [2].

and in the excavation-damaged zone surrounding the tunnel, and possibly sorption of gaseous oxygen by the bentonite [2,54]. It thus seems as if not only is the aerobic phase much shorter than previously believed, but also that the initially trapped O_2 may be consumed by processes other than canister corrosion. If true, this observation has potentially profound implications for the performance of HLW/SF canisters since it is only during the initial aerobic phase that rapid localized forms of corrosion are believed to be possible for a number of candidate canister materials.

10.5 Summary

In situ corrosion experiments on candidate canister materials have been conducted in European URLs for the past 30−40 years. The main benefit of such experiments is an increase of realism achieved by contact with the actual host rock, porewater, and microbial communities, as well as the ability to increase the scale. However, each country tends to conduct experiments that are designed to mimic the national disposal concept. Nevertheless, broad conclusions can be drawn from these dissimilar activities that provide significant contributions to confidence building in long-term predictions, demonstrate the robustness of the different national disposal concepts, and confirm the corrosion rates that are used in safety assessment.

In situ experiments have highlighted the importance of the experimental design, as relatively small differences in design can lead to unexpected phenomena. For example, the importance of confinement in order to decrease microbial activity and achieve low corrosion rates has been shown repeatedly. Furthermore, in situ corrosion experiments have provided insight to repository design and optimization that would not have been possible if the tests were not done in the actual host rock.

On the other hand, it has been demonstrated that in order to maximize the usefulness of the obtained results, corrosion-specific experiments with well-defined exposure conditions are needed. Otherwise, interpretation of the results becomes exceedingly difficult. Full-scale experiments under realistic conditions provide the maximum benefit and can produce additional insights that are sometimes unexpected.

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