

Quality assurance - LOT meeting 3

This information was presented at the third meeting of the quality assurance for the LOT project with focus on Interpretation of results. SKB had received questions before the meeting and all the questions and answers are documented below. The discussion will be documented in minutes and is not included in this document.

- (i) Management system & project management (2020-11-05)
- (ii) Retrieval, sampling, handling of samples & analysis (2020-11-13)
- (iii) **Interpretation of results (2020-11-27)**

Quality management system

1. Selecting suppliers

What evaluation criteria do you use when selecting SKB's external supplier companies (e.g. KIMAB, Swerim, Clay Technology)? Do you have minimum requirements for respective company expertise and profile?

SKBs reply/comment: *SKB prefers that the suppliers are ISO-certified. A supplier evaluation is performed before contracting a new supplier and is renewed regularly to assure that the company still meets SKB's expectations. In the evaluation the different criteria are described in 1056110 – Inköpsinstruktionen (Purchase instruction), and these criteria regard:*

- *Economy*
- *Quality assurance*
- *Environmental impact*

After delivery an evaluation of the new company used is done by the client according to a template provided by the procurement unit at SKB. For previously evaluated companies, additional evaluations should be made if called for by new experiences. These procedures are in place to ensure that past experiences are taken into account when considering a company for additional assignments.

Minor companies and sole proprietorships do not necessarily have ISO-certifications and are then chosen for their unique expertise. The evaluation is then based on CVs, level of education, publications in the scientific literature, etc.

2. Collaboration with consultants

How long has SKB collaborated with KIMAB, Swerim, and Clay Technology?

SKBs reply/comment: *The relationship between SKB and these companies has long history. SKB (and its predecessor the KBS-project) has collaborated with the Swedish Corrosion Research Institute (Korrosionsforskningsinstitutet) and the Swedish Institute for Metals Research (Institutet för Metallforskning) at the Royal Institute of Technology (KTH) since 1977. Corrosion studies were performed from 1977, and creep studies started in 1984. These two institutes then joined and*

formed KIMAB, later Swerea KIMAB. A couple of years ago the company was divided into RISE KIMAB and Swerim.

Clay Technology was formed in 1988 and SKB have been using the company from start. The company was formed by parts of SGAB (Sveriges Geologiska AB, a state-owned company formed in 1982) with which SKB collaborated before Clay Technology was formed.

3. Report procedures

Do contracting companies provide internal company reports to SKB which are then further processed within SKB to SKB TR- or R-reports?

SKBs reply/comment: *Yes, in some cases, depending on the degree of involvement of SKB's experts in the actual work done. When SKB experts are involved in the work they are normally involved at an early stage of experimental planning, analysis and reporting. In such cases the SKB expert is usually a co-author of the report. For other reports the only post-processing is editorial, i.e. typesetting and printing of the report.*

4. External data deliveries

How are data deliveries from contractors controlled? That is, are data post-processed for recording in Sicada/use in reports?

SKBs reply/comment: *Data is sent (by e-mail or via ftp) by the contractor and stored in Sicada, and a resource responsible for the work approves/releases the data in SICADA. With respect to post-processing, it depends on the data type. For example, temperature is stored as raw data, while other data are stored both as a raw data measurement files and calculated results in a template. For reports, calculated results are generally plotted or presented in tables. A general principle is that no data should be omitted. If it is obvious that e.g. a sensor is malfunctioning (for example showing unrealistic or unphysical values), it shall be documented that data from this sensor is removed and why.*

Interpretation of LOT corrosion analysis and test conditions

5. Corrosion - function of time

What can be said about the extent of copper corrosion in the LOT test as a function of time considering all available data? Are there clear causes for variability apart from the apparent dependence on temperature? Could there be non-quantifiable causes for variation related to the design of the experiments and, if so, which are expected to be the most significant?

SKBs reply/comment: *Corrosion on the warmest parts of the pipes was estimated to be of the order of 10 µm, with a few µm deeper corrosion on the warmest parts of A3 (20 years) than for A2 (6 years). This is probably because O₂-induced corrosion proceeds beyond the depletion of O₂ itself, since the intermediate oxidant Cu(II) prevails on much longer time scales (King et al. 2010, King and Kolář, 2019). However, it can not be excluded that the available amount of O₂ differed between the test parcels. On the colder parts of the pipes, there was no significant difference between the A2 and A3 parcels.*

For the coupons, gravimetric data is available from several test parcels and corrosion could be quantified with standardised methods. Two observations may be noted regarding variability; 1) The corrosion depths varied from 0.6 to 4.7 µm and were highest in the 1-year parcels (A0 and

S1), intermediate in the 6-year parcel (A2) and lowest in the 20-year parcels (S2 and A3). The corrosion was thus inversely proportional with time and correlation of measured corrosion depths (mass-loss) with temperature was very weak, indicating that there were other factors than time and temperature that controlled the corrosion in these experiments. 2) In the test parcel ABM 5 (another Äspö bentonite experiment, very similar to LOT), the variation in corrosion depth by mass-loss was 2.3 to 5 μm (Gordon et al. 2018), despite the fact that all specimens had the same temperature (ca 80 °C) and were exposed for the same time (5 years). It is not known exactly what causes this variability in LOT and ABM, but the most reasonable explanation is considered to be heterogeneous distribution of O₂ and/or heterogeneous resaturation of the bentonite clay. Variations in the initial surface conditions of the copper specimens, especially for the pipes, can not be disregarded, e.g. regarding roughness and/or the initial oxide layer.

6. Corrosion - highest temperatures

SKB has not measured the extent of corrosion on the part of the copper tube exposed to the highest temperatures. Why? What could be expected if these tube sections were analysed?

SKBs reply/comment: *The corrosion of the warmest parts of the copper pipes has been measured by estimates based on the concentration of copper in the bentonite pipes (e.g. in block 9 and 11 for A3, see Table 3-19 in Johansson et al. 2020). Examination of the pipe surfaces was done for the pipes in blocks 21-23, since these were carefully handled during extraction of the coupons contained within the same bentonite blocks, in order to avoid damaging (scratching) the surfaces.*

It may be noted that the temperature at the pipe surfaces examined metallographically was 70-80 °C for A3, which is not far from the peak temperature of 95 °C for any copper canister in the KBS-3 repository. On the other hand, the maximum temperature in A3 was 120 °C, which is higher than what is relevant for the canister in the repository. Initially, the canister surface in the repository will be ca 50 °C and it will take about a decade to reach the maximum temperature after which the temperature decreases slowly.

It is possible that the warmest part of the A3 pipe could be more rough or have slightly deeper pits than the examined part (depending on how the extent of these pits is influenced by corrosion). However, it should be noted that the deepest pits found on the pipe in A3 were only 25 μm , while the expected range of pits during initially oxidising conditions in the KBS-3 repository would be up to a few hundred μm , and with a low probability of pits even up to ca 1 mm (Briggs et al. 2020). Pipe material from LOT S2 and A3 has been saved for the possibility of further metallographic examination. It is, however, unlikely that the confirmation of deeper pits on the warmest parts of the pipe in A3 would change any conclusions regarding localised corrosion under the initially oxidising conditions of the repository.

7. Copper in bentonite - XRF

Do the bentonite copper content measurements by XRF provide an accurate measure of the local extent of corrosion on the copper tube? Would consideration of corrosion products left on the copper tube significantly affect the results?

SKBs reply/comment: *The estimate from the XRF analysis of clay near the coupons showed that the mass of copper found in the bentonite clay was in the range 0.011-0.018 g. This is not far from the mass-losses of the coupons which were in the range 0.009-0.024 g, and which correspond to corrosion depths of 0.6-1.3 μm . The “error” in this comparison would be the adherent corrosion products which are included in the gravimetric analysis but not in the Cu in clay analysis. However, the oxide films on the coupons were generally very thin, typically around 1 μm , at some positions less, and locally sometimes up to a few μm (see e.g. Fig 4-2 and Fig B-38 in Johansson et al. 2020). There was no apparent difference in oxide films on the coupons A3/K (50 °C) and*

S2/N (30 °C), as seen in the micrographs in Appendix B. It may be further noted that there was no obvious difference in the thickness of adherent corrosion products on the examined pipe samples (Appendices F and G in Johansson et al. 2020). Some micrographs show adherent layers of bentonite (high Si), while corrosion products were typically around 1 µm thick, sometimes less and locally sometimes more corrosion products in or near pits or surface defects. This was despite the fact that the temperature was higher in A3 (70-80 °C) than in S2 (50-60 °C), and despite the fact that both lighter and darker areas were examined for each test parcel (Figure G1-G5 in TR-20-14).

Laboratory studies in the Canadian program have shown that the estimate of corrosion from copper content in the clay, sometimes need to be multiplied by a factor to match gravimetric results. This factor has been estimated to range from 1 to 19 in the different experiments made (Litke et al. 1992, King et al. 1997). While the experiments in Litke et al. (1992) used a 50:50 sand-bentonite mixture and had an initial O₂ inventory of ca 30 mol/m² copper area, the experiments in King et al. (1997) used compacted bentonite without sand and had less than 1 mol/m² copper, which is closer to the initial conditions in LOT. The factors derived in the study by King et al. (1997) varied in most cases within the range 1-1.7. The fact that many of these values were close to 1 is in agreement with the general picture from LOT in which the adherent oxide film was mostly very thin.

8. Oxygen consumption - microbes

It has been claimed in the LOT context that the initial oxygen content available during the LOT-experiments was rapidly consumed by microbial processes before the oxygen had a chance to react with the copper. What is SKB's position regarding this claim? What knowledge can be gained from SKB's other experiments regarding microbial oxygen consumption, pyrite oxidation and other reactions in bentonite clay?

SKBs reply/comment: *The bentonite clay in LOT was initially cold and unsaturated, conditions under which microbial O₂ consumption is very inefficient (Birgersson and Goudarzi 2018, Giroud et al. 2018). When the heaters were turned on the temperature of the copper surface increased rapidly from rock temperature to ca 40 °C and then continued to increase. As indicated by laboratory studies, copper corrosion under aerobic conditions and temperatures 50-80 °C can occur rather rapidly (Litke et al. 1992, King et al. 1997). This supports the view that O₂ may have been consumed by corrosion before the microbial consumption started. Oxidation of pyrite is not significant at rock temperature but is known to occur at 55 °C. The occurrence of pyrite oxidation would however be difficult to confirm, which is further discussed in the reply to Q9.*

9. Oxygen consumption - other processes

If all the oxygen was not consumed in the experiment, could a certain fraction of the available oxygen have been consumed by processes other than copper corrosion? If so what is an approximate estimate of this fraction? Is there a formation of sulphate which could indicate pyrite oxidation?

SKBs reply/comment: *Formation of sulphate from pyrite oxidation is likely to occur, however a bit difficult to verify, as the bentonite originally also includes gypsum (Ca-sulphate) and the sulphate moves in the bentonite, typically towards the central heater. Possibly the total sulphate content could be measured. Another strategy could be to look for disappearance of pyrite in XRD, however this is not trivial as the pyrite content is low already at the start. In Callovo-oxfordian (COX) clay, which is a clay stone rich in pyrite, signs of pyrite oxidation in the field experiment ABM1 was observed based on increasing Fe(III)/Fe(II) ratio, however this was not studied in detail as it was not the purpose of the study (Svensson and Hansen, 2013).*

10. Availability of oxygen

Could there have been a slow leakage of oxygen from the tunnel through seals, fractures in the rock, the EDZ, through holes next to cables and pipes etc.? (Onset of reducing conditions does not *per se* exclude in-leakage if the prevailing redox reactions consuming oxygen are reasonably well buffered).

SKBs reply/comment: *The weld between the bottom plate and pipe was pressure tested with He gas before the experiments were installed (Sandén and Nilsson, 2020). It seems unlikely that significant leakage could have occurred through concrete and clay, however, considering the large number of cables going through the concrete and around the test parcels it can not be completely excluded that some leakage could have occurred.*

11. Added groundwater- influence on oxygen

Could groundwater added to the LOT experiments have consumed oxygen through its reducing capacity? Is there knowledge of the reducing capacity of this groundwater (e.g. Fe(II) content)? If so how could addition of groundwater have affected the oxygen content available for copper corrosion?

SKBs reply/comment: *The Fe(II) content of the groundwater that is supplied to LOT is low (around 70 ppb). Since the exchange of groundwater with the LOT-packages is limited the Fe(II) can be assumed to have negligible effect on the oxygen consumption.*

12. Water filling procedure

Were all slots and gaps completely filled with groundwater at the onset of the experiments (i.e. when the heaters were switched on)? For how long were the slots and gaps open? What was the pathway for water to enter the gaps (i.e. from titanium tubes and rock)? What is known about the groundwater inflow rates in the “deposition holes”? Is it possible to identify any water conducting feature in spite of the drilling near the holes?

SKBs reply/comment: *The (natural) water inflow rates were measured at different depths in the bore holes for the LOT test parcels. The general conclusions from the pilot hole characterization program were that the water inflow was low, and that the water inlet points were few in all holes (therefore it was decided to use groundwater from the nearby hole, see below). The average water inflow to the borehole where test parcel S2 should be installed was ca 1 ml/min, which is nearly two orders of magnitude higher than for the other boreholes (Table 2-1 in Sandén and Nilsson 2020).*

Before the start of the heaters and the water filling procedure, the Ti-tubes were open to the Äspö tunnel for ca 4 month in the S2 and A3 test parcels (Table 3-1 in Sandén and Nilsson 2020).

After installation of the test parcels in the holes, there was a remaining air-filled gap between bentonite blocks and rock surface with a width of 10 mm, and another air-filled gap between bentonite blocks and the central copper tube with a width of ca 1 mm. These gaps were slowly water filled (on February 2, 2000) in parallel with the onset of heating. The filling was made with groundwater from the adjacent borehole (HG0038B01) by use of the fixed installed Ti-tube and bottom filter placed in the sand below the parcel and close to the rock wall. The valve connected to the bottom filter was closed at the time when the groundwater had reached the uppermost filter (filter in block 32), which until then was open to the Äspö tunnel. This filter was then instead connected to the ground-water supply. This inflow point is assessed to simulate a point inflow from a water bearing fracture in the rock. The test parcels have had access to pressurised water from this point inflow during the entire test duration.

13. Water inflows in the LOT boreholes

Are there known differences between the LOT holes regarding water inflow and saturation? What is the time scale of full resaturation and is there an appreciable variability between the holes?

SKBs reply/comment: *The natural flow was described in the reply to Q12. Reaching full saturation and swelling pressure of the bentonite clay generally took years. For blocks 8 and 14 in LOT A3, near the hottest part of the copper pipe, the process was particularly slow, taking 4 – 6 years to reach the final pressure (Sandén and Nilsson 2020). This can be compared with LOT A2, in which the saturation in blocks 8 and 14 took less than two years (Karnland et al. 2009).*

SKB's position with respect to copper corrosion and alternative interpretations

14. Corrosion kinetics

At what point does the oxidic corrosion of copper become diffusion controlled due to the formation of corrosion products? Is diffusion control of relevance (or mixed kinetics) as a rate limit for the initial phase of LOT with oxidic corrosion?

SKBs reply/comment: *Diffusion control could mean either anodic diffusion control (i.e. the diffusion of either copper cations across a passive Cu_2O film or of dissolved Cu(I) diffusing in the buffer pore water) or cathodic diffusion control (i.e. diffusion of O_2 either through the buffer or across a precipitated corrosion product layer). Different experiments have indicated different types of diffusion control. For example, measurements of the depletion of O_2 with time in King et al. (1997) clearly indicated diffusion-limited O_2 consumption, which suggests that the cathodic reaction is diffusion controlled. In that study, the limiting step was probably diffusion through the buffer, rather than through a thin corrosion product film, as the buffer was compacted in situ (i.e. there were no air-filled gaps). On the other hand, anodic transport control may have been possible in Litke et al. (1992) because of the high amounts of O_2 in the tests. While the experiments in King et al. (1997) may be applicable to the coupons in LOT, the situation for the copper pipes in LOT is more complicated due to the fact that air-filled gaps may have been present initially and when these had been depleted of O_2 , the oxidant, O_2 or Cu(II) , was only available by diffusion through the bentonite clay.*

15. Corrosion -temperature dependence

What is the temperature dependence of copper corrosion rate for the relatively unexposed copper surfaces put in the LOT experiment (activation energy)?

SKBs reply/comment: *For the copper coupons, the correlation of corrosion depth (or rate) with temperature was very weak. This may reflect that the corrosion was controlled by diffusion through the clay. However, it must also be noted that the temperature did not differ as much between the coupons as for the pipes. For the copper pipes, there was a clear temperature effect on the measured corrosion depths (and thus on the integrated corrosion rates) as shown in Figure 4-1 in Johansson et al. (2020). Since the integrated corrosion rates are determined for a very long period of time (20 years) during which the corrosion process goes through different mechanistic phases (O_2 , Cu(II) , sulphide) with different kinetics, it is unclear what a detailed kinetic analysis of activation energies based on integrated rates would mean.*

16. Corrosion in sand

What are differences in between corrosion of copper in sand and in bentonite (of relevance for interpretation of corrosion on the tube bottom plate)?

SKBs reply/comment: *This has not been investigated, since sand is not a material that will be used in the KBS-3 repository, it was only used in the specific LOT experiments. The verification of solid Cu(II) corrosion products adherent to the bottom plate, but not on other copper surfaces in LOT, may be due to ion exchange between corrosion products and bentonite clay, which does not occur with sand.*

17. Corrosion kinetics, oxic-anoxic conditions

It has been claimed in the LOT context that corrosion of copper will not slowdown in response to a shift between oxic and anoxic conditions. What is SKB's position on that?

SKBs reply/comment: *Experimentally, it has not been possible to distinguish the time dependence of the corrosion rate in the presence of O₂ versus the presence only of Cu(II), although the latter phase is expected to be longer (King et al. 2010). However, when O₂ has been depleted and the resulting Cu(II) intermediate has reacted, the only oxidant available in the deep ground water environment is sulphide, for which transport limitations will control the long-term corrosion rate. The integrated corrosion rates that can be calculated from corrosion depths obtained from copper coupons and pipes in the LOT series, clearly indicate that the integrated rate is decreasing with time. This is discussed in sections 4.2.1 and 4.2.2 in Johansson et al. (2020). As regards the possibility of corrosion of copper in pure, O₂-free water, it is SKB's clear position that this process occurs to an extent that is compatible with established thermodynamic data, which is completely negligible in the LOT context, see further Hedin et al. 2018 and SKB 2019, Chapter 4.*

18. Corrosion products, oxic-anoxic conditions

It has been claimed in the LOT context that the formation of the main detected corrosion product cuprite (Cu₂O) in LOT A2 and S2, and also other typical corrosion products in similar experiments (malachite Cu₂(CO₃)(OH)₂, para-atacamite Cu₂Cl(OH)₃) may be related to anoxic conditions. What is SKB's position regarding this issue? What are SKB's key arguments? Has knowledge of the thermodynamic properties of these phases been utilized to address such issues?

SKBs reply/comment: *In order to form corrosion products, in such amounts to precipitate solid phases, some other oxidising species than water is needed (the dissolved copper oxidised by water is negligible; Hedin et al. 2018, SKB 2019). For this evaluation thermodynamic data is used to investigate what phases that can form under different conditions. For example, the copper oxide corrosion product Cu₂O is formed under conditions where the redox potential $E_h > 0$ V SHE (at 25 °C, for pH up to 8, and a total copper concentration in solution of 10⁻⁶ M). To form Cu(II) solid phases even higher potentials are required. This can be seen from Pourbaix diagrams (Puigdomenech and Taxén 2000), but can also be evaluated with more detailed speciation calculations, that has been done e.g. for corrosion in high chloride concentrations (Lilja et al. 2020), still using the same type of thermodynamic data. The claims that the solid corrosion products are related to anoxic conditions, may depend on the used definition of "anoxic conditions". For the LOT experiment (as well as in the bentonite buffer in the repository) the redox potential would be determined most probably by iron compounds and be in the range of that in groundwater (around -0.2 V; SKB 2011), when all O₂ is consumed. Such potentials are not compatible with formation of either copper oxides or paratacamite (or malachite). The observation of oxides and paratacamite in LOT is though consistent with thermodynamic data for the initial conditions with O₂ (high E_h). (Malachite would be formed with a water composition with slightly lower chloride concentration and higher carbonate concentration.) Even if the*

development of reducing conditions does not support formation of e.g. paratacamite, this does not exclude that compounds already formed may remain kinetically stable also during reducing conditions.

19. Corrosion products- Cu(II) phases

In King's review, a presence of Cu(II)-phases is suggested. According to established knowledge, ordinary copper corrosion in an oxic environment involves formation of a double-layer of Cu₂O and CuO on top of the metal, with the monovalent oxide forming closest to the metal surface. To what extent does the presence of the buffer affect these reactions? What is the significance of an absence or presence of Cu(II)-phases for the interpretation of LOT? It has been claimed in the LOT context that a lack of Cu(II) suggests that corrosion has been anoxic. What is SKB's position on this issue?

SKBs reply/comment: *As elaborated on in the answer to Q18, the oxidation state of corrosion products, more oxidising conditions (more positive Eh) supports the formation of Cu(II) compounds (e.g. CuO in fresh water or paratacamite, Cu₂(OH)₃Cl, in chloride-rich groundwater), while less oxidising conditions (less positive Eh) results in the formation of Cu(I) corrosion products (e.g. Cu₂O or CuCl₂⁻). In aerobic systems, it is common to get a bilayer structure with a Cu(II) phase on top of Cu₂O, and this was found in the copper-bentonite experiments in both Litke et al. (1992) and King et al. (1997). The bentonite tends to adsorb the Cu(II) and, hence, lower the tendency for Cu(II) precipitation at the copper surface. In Litke et al. (1992) the initial [O₂] was high (30 mol/m² Cu) and the average corrosion depth was ca 40 µm, and precipitated Cu(II) was clearly visible as blue-green corrosion products. In King et al. (1997), the initial [O₂] was lower (<1 mol/m² Cu) and the fraction of Cu(II) in the corrosion product was in the range 1-56%, while the steep copper profiles in the bentonite clay adjacent to the copper surfaces implied the presence of Cu(II) adsorbed in the clay. LOT seems to be more similar to King et al. (1997), i.e. no visible adherent Cu(II) products but steep Cu profiles in the adjacent bentonite clay. See also answer to Q16.*

20. Hydrogen embrittlement

One of key issues raised by the Swedish Environment Court is hydrogen embrittlement of copper. Are there any results of relevance to this issue for the LOT S2 and A3 phases?

SKBs reply/comment: *Analysis of hydrogen levels in the copper pipes from LOT S2 and A3 (section 3.4.2 in Johansson et al. 2020), shows that hydrogen is only present in or near the surface of the material, which is also where corrosion products and bentonite deposits are present. Comparison of bulk levels of hydrogen of the S2 and A3 pipes with a reference pipe showed very low levels of hydrogen and no significant difference between the pipes. Having said this, it may be noted that the only process which could hypothetically lead to hydrogen uptake by copper under the conditions in LOT, is the long-term corrosion by sulphide (H₂S/HS⁻), and as is evident from the results in Johansson et al (2020), the extent of sulphide corrosion in LOT was very limited.*

21. FEBEX - LOT

Are there any key findings from the FEBEX experiments are of relevance for the interpretation of the LOT results?

SKBs reply/comment: *The results from Febex are regarded as part of the general scientific knowledge of copper corrosion under early repository conditions dominated by O₂-induced corrosion (Wersin and Kober 2017). The results, e.g. regarding corrosion products and corrosion morphology, are discussed in Johansson et al. (2020) and will be integrated in the safety assessment PSAR for the spent fuel repository.*

A few detailed results may be worth mentioning in this context. The mass-loss of the Febex coupon 4A2 corresponded to an average corrosion depth of 8.5 μm , while the deepest pit observed on the Febex coupon 4A1 was ca 90 μm . These numbers are both larger than the corresponding values for the coupons in LOT, which may be due to a combination of higher temperature, larger clay volume (more O_2) and an extended oxic period in Febex as compared with LOT. It may be noted that Febex differed from LOT in several aspects, for example there was no sulphur on the coupons in Febex (while low levels of sulphur were found on all copper surfaces in LOT), there were clear signs of blue-green Cu(II) corrosion products on the coupons in Febex (not present generally in LOT S2 or A3), and Febex is thought to have had a longer oxic period initially (possibly due to leakage from the tunnel).

Concluding remarks by SKB

In the context of the above questions from SSM, SKB would like to make the following summarizing points regarding the interpretation of copper corrosion in the LOT series:

Purpose with the LOT experiment

- Since the LOT experiments were designed by clay scientists with the purpose to study the behavior of bentonite clay under repository-like conditions, the experiments can only give limited information about copper corrosion. In order to be clear about this, a number of limitations of LOT, if considered as a corrosion experiment, are discussed in Section 1.5 in Johansson et al. (2020).
- There is no information available concerning the initial development of redox conditions in the LOT experiments, and, consequently, the development of the corrosion process can not be described in detail.

Oxygen consumption

- There is a large uncertainty considering the amount of O_2 (from air) that has been available for corrosion.
- It is considered likely that the copper pipe surfaces consumed a large fraction of the initially available O_2 when the heaters were turned on and during the following months during which the temperature of the pipes increased from 40 °C to 90 °C or higher.
- It is considered likely that the copper pipes consumed most of the O_2 in the unsaturated clay system faster than chemical processes in the clay (e.g. oxidation of pyrite) since the copper surface had a higher temperature than the outer parts of the bentonite blocks.
- Microbial consumption of O_2 is not regarded as efficient in unsaturated bentonite clay.

Evaluation of corrosion

- Since the roughness of the copper surfaces in LOT were not characterized prior to the experiments (one of the limitations of LOT if regarded as a corrosion experiment), localized corrosion can only be pessimistically evaluated by assuming that the topography observed is solely due to corrosion. However, even under that assumption, the observed pits are consistent with the expected corrosion morphology under initially oxidizing conditions in the repository.
- Given the uncertainties due to the limitations of LOT as a corrosion experiment, the results are consistent with the conceptual corrosion model applied by SKB in the assessment of post-closure safety for the spent fuel repository.
- In contrast to what is predicted by established science and thermodynamic data, it has been suggested that copper corrodes in pure O_2 -free water, i.e. by reactions between copper and water molecules. It is emphasized that this hypothesis can not be evaluated in a complex

field test like LOT, in which air (O₂) was initially available and since groundwater is not pure water. This hypothesis has instead been thoroughly evaluated in careful laboratory experiments, which have been published in the scientific literature.

- The detailed evaluation of corrosion in SKBs safety assessment is based on numerous studies (laboratory experiments, models, and field tests) of different aspects of copper corrosion under repository conditions (radiation, O₂, sulphide, microorganisms, groundwater etc) and is not dependent on a single experiment like LOT, especially since it was not designed for detailed studies of corrosion.

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