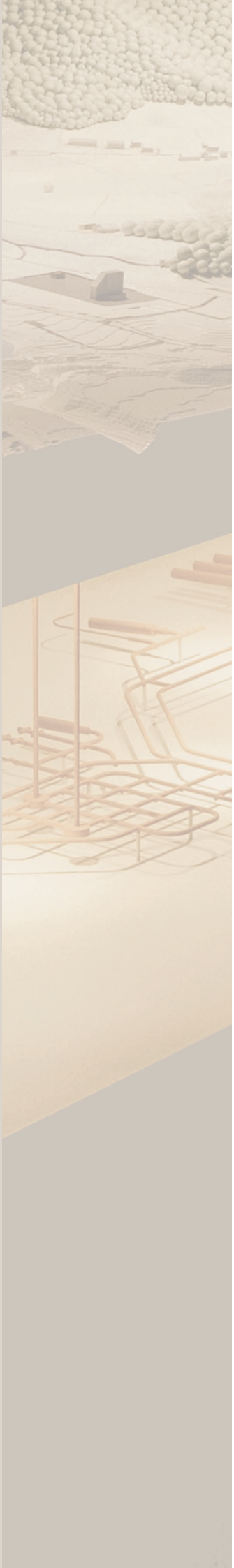

nagra.

ARBEITSBERICHT NAB 23-22

Definition of Reference Corrosion Rates for Performance and Safety Assessments

December 2023

Nagra | National Cooperative for the Disposal of Radioactive Waste
Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | nagra.ch

nagra.

ARBEITSBERICHT NAB 23-22

Definition of Reference Corrosion Rates for Performance and Safety Assessments

December 2023

N. Diomidis[1], T. Guillemot[1] & F. King[2]

[1]Nagra

[2]Integrity Corrosion Consulting Ltd.

KEYWORDS
Metals, corrosion rates, gas generation

Nagra | **National Cooperative for the Disposal of Radioactive Waste**
Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | nagra.ch

Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information..

Abstract

This report defines the reference corrosion rates to be used in performance and safety assessments of a deep geological repository in Opalinus Clay. The corrosion rates can be used for: (i) the estimation of gas generation rates; (ii) the calculation of release rates of radionuclides from activated metals; (iii) the prediction of the rate of anaerobic corrosion of carbon steel canisters for spent fuel and high-level waste. The report is based on a critical review of reports and papers available in the open literature and of the results of corrosion and gas generation studies performed as part of the Nagra programme.

Additional data have become available since the last such review in 2014, resulting in an update of the reference rates. Improvements in the mechanistic understanding of the corrosion processes involved, as well as the availability of more sensitive measurement techniques and longer accumulated exposure periods for continuing experiments, have resulted in improved definitions of the corrosion rates. Reference corrosion rates are now defined for various classes of alloy (iron and carbon steel, stainless steel and Ni-based alloys, aluminium, lead, Zircaloy, copper, zinc, and magnesium) in both alkaline and near-neutral pH conditions, as well as for carbon steel in contact with compacted bentonite.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ACW	Artificial Cement Water
API-MS	Atmospheric Pressure Ionisation coupled with Mass Spectrometry
ATW	Alpha-Toxic waste
BFS	Blast Furnace Slag
CEM	Standard designation for a type of cement composition
GC	Gas Chromatography
GC-MS	Gas Chromatography coupled with Mass Spectrometry
GC-TCD	Gas Chromatography coupled with Thermal Conductivity Detector
HLW	High-Level Waste (spent fuel assemblies and high-level waste from reprocessing)
L/ILW	Low- and Intermediate-Level Waste
MS	Mass Spectrometry
OPA	Opalinus Clay
OPC	Ordinary Portland Cement
OPC/BFS	Ordinary Portland Cement/Blast Furnace Slag
RH	Relative Humidity
SF	Spent Fuel assemblies
YCW	Young Cement Water

1 Introduction

1.1 Scope of this report

The main objective of the present report is to define representative corrosion rates for relevant metallic materials under the conditions expected in a deep geological repository in Opalinus Clay according to the Swiss disposal concept. This goal is achieved based on a detailed literature review and the development of criteria for the selection of relevant studies. The review includes data from studies published in peer-reviewed articles, as well as in public reports from waste management organizations and elsewhere. As such, this report is an update of Diomidis (2014).

Corrosion is an irreversible interfacial reaction of a material with its environment, resulting in the loss of material or in the dissolution of one of the constituents of the environment into the material (Landolt 2007). Corrosion is a system property and thus the corrosion behaviour of a material depends on its chemical, physical, and mechanical properties, as well as the chemical, physical, and mechanical conditions of the environment. As a result, the mechanism and rate of corrosion of a metallic material can evolve with the conditions prevailing in the near field of a deep geological repository.

Corrosion is a process that is important for the assessment of the performance and safety of a deep geological repository as it can contribute to the following phenomena:

- Breaching of disposal canisters. Canisters for the disposal of spent fuel (SF) and high-level waste (HLW) will gradually corrode in the repository, and eventually, under the combined effects of environmental degradation and applied or residual stresses will fail allowing the ingress of porewater. The rate and mechanism of corrosion of the canister material are important input parameters for the prediction of the lifetime of the canisters. Further information on canister corrosion and lifetime prediction is provided in Nagra (2024b), in prep. for the reference carbon steel canister and in Diomidis & King (2022) for an alternative copper-coated disposal canister.
- Generation of gas. In the absence of oxygen (O_2), the cathodic half-reaction of metallic corrosion involves the reduction of water which generates hydrogen (H_2). Gas generation, migration and accumulation in a deep geological repository has the potential to influence the performance of engineered and natural barriers. As such, the rate of corrosion, which defines the rate of gas generation from metallic materials, is an important input parameter in performance assessment. Further information related to the assessment of gas-related phenomena is provided in Nagra (2024f), in prep.
- Release of radionuclides. Activated metals tend to release the majority of their radionuclide inventory congruently with corrosion. Thus, the corrosion rate defines the rate of radionuclide release and is an important factor in consequence analyses. Further information on the assessment of radionuclide release is provided in Nagra (2024a), in prep. and Nagra (2024g), in prep.

The following sections of Chapter 1 provide a short overview of the metal inventory in the planned deep geological repository, and the expected near-field environment to which the metallic materials will be exposed. Chapter 2 describes and substantiates the selection process for the identification of relevant studies from the literature with the aim of obtaining a corrosion dataset that is representative of the Swiss deep geological repository environment. The selected studies and the reported corrosion rates are presented in Chapter 3. A summary of the defined corrosion rates is presented in Chapter 4.

1.2 Repository layout

The current Nagra project for the general license application in Nördlich Lägern envisages two disposal facilities, one for HLW and SF, and one for low/intermediate-level (L/ILW) and alpha-toxic (ATW) waste, co-located at the same site, i.e., in a so-called "combined repository".

The underground part of the combined repository will be constructed in Opalinus Clay (OPA) at a depth between 800 – 900 b.g.l. The generic layout of a combined repository is given in Nagra (2021) (Fig. 1-1). It will include a series of dead-end emplacement drifts for HLW/SF and dead-end emplacement caverns for L/ILW and ATW. The HLW emplacement drifts will be spatially separated from L/ILW emplacement rooms such that interactions between the two parts are minimised.

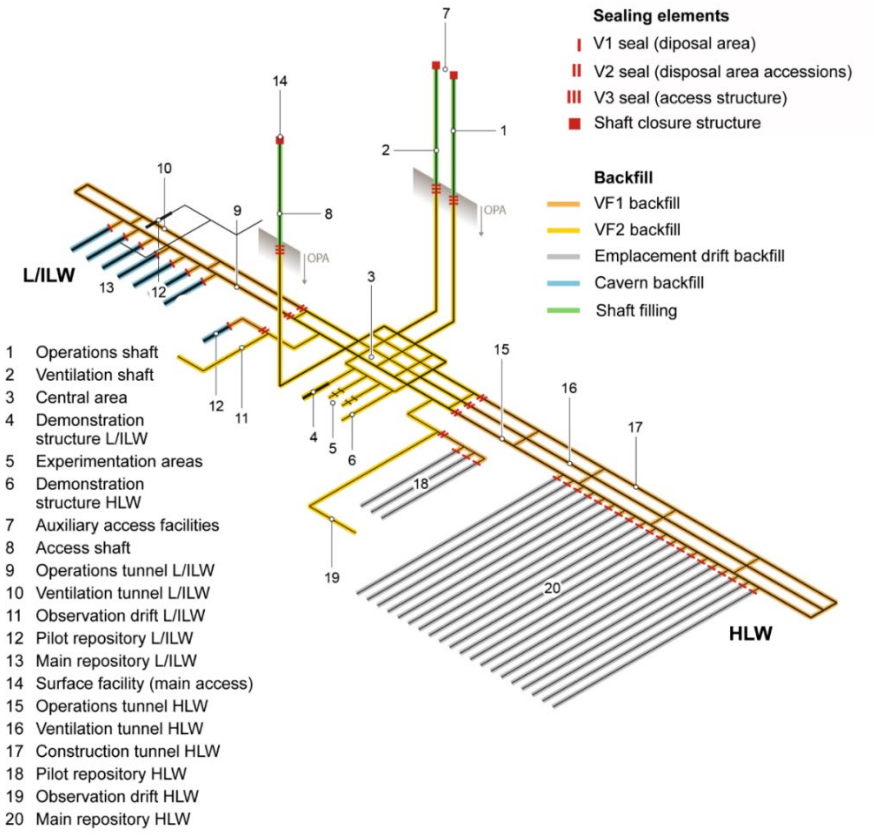

Fig. 1-1: Generic layout of the underground facilities of the Swiss provisional deep geological repository

From Nagra (2021)

Operational L/ILW and ATW will be mainly solidified in cement, packed into 200 L drums and placed into disposal containers made of concrete and heavily armoured with rebars (Nagra 2024d, in prep.). L/ILW and ATW from decommissioning will be emplaced directly into the concrete disposal containers. The void space within the disposal containers will be filled with a highly flowable mortar (Nagra 2024d, in prep.).

SF and vitrified HLW in their fabrication flasks will be loaded into disposal canisters, which, according to the current Nagra repository project, will be made of carbon steel. The disposal canisters will be around 5 m (SF) and 4 m (HLW) long. They will each have a diameter of around 1.1 m (SF) or 0.7 m (HLW), and a wall thickness of 14 cm (Nagra 2024b, in prep.).

1.3 Near-field environment of the L/ILW repository section

The aspects of the phenomenological evolution of the L/ILW repository near field that are relevant to metal corrosion in the L/ILW repository part are briefly summarised in this section. More details can be found in Nagra (2024d), in prep. and Nagra (2024e), in prep.

The ambient temperature for the L/ILW part of the repository in the proposed siting region of Nördlich Lägern at a depth between 800 – 900 b.g.l, is expected to be in the order of 45 °C. Initially, the temperature in the L/ILW backfilled caverns will increase to a maximum of 10 – 15 °C above the ambient value, primarily due to cement hydration. The temperature peaks within a few months after backfilling with mortar, and then decreases over several years to become similar to the ambient temperature in the surrounding rock. In the long-term, the temperature of the L/ILW repository near field is expected to be stable as no influence from the HLW repository is foreseen.

After the sealing of each emplacement cavern, O_2 in the entrapped atmosphere will be consumed by aerobic corrosion, degradation of organic materials and other processes (e.g., sorption, or pyrite oxidation). After O_2 depletion, the L/ILW repository near field will remain anoxic.

Initially, little free water is expected. However, it is assumed that the L/ILW emplacement caverns will have a high relative humidity and be only locally partially saturated. In the early post-colure period (first few 100s of years) saturation in the caverns gradually increases due to inflow from the host rock. Later on, and up to a few 10'000s of years, the saturation decreases due to gas generation and accumulation. In the late post-closure period, water saturation increases again as gas generation decreases. In general, any water accumulation in the caverns will happen very slowly and will be confined to the bottom parts of the caverns, while de-saturated conditions, with pore space occupied by the remaining gas, will persist in the upper parts of the caverns.

Highly alkaline near-field conditions will prevail due to the ordinary Portland cement (OPC) used as a backfill and the other cementitious materials used in construction, waste containers and infill. However, the buffer capacity of the cement can be reduced by interaction with the CO_2 produced by organic degradation (carbonation) and/or with the fine fraction of the siliceous aggregates (pozzolanic reaction). Cement degradation can be divided into 4 main stages:

I. The freshly hydrated cement/concrete stage, with a high pH pore water between 12.5 and 13.5 due to the significant amounts of dissolved alkali hydroxides.

II. The portlandite ($Ca(OH)_2$) stability stage, characterised by a lower ionic strength and saturation equilibrium with portlandite, which buffers the porewater pH at ~ 12.5.

III. The low-pH stage, where the portlandite is completely dissolved by pozzolanic reaction or carbonation. The portlandite is converted by modified calcium silicate hydrate (C-S-H) phases and porewater pH values are between 12.5 and 10.

IV. The fourth stage is the final cement degradation state where all Ca-bearing cement phases are fully dissolved. This state may be reached only when significant amounts of CO_2 have been involved in the carbonation process.

In a deep geological repository, concrete degradation will not be homogeneous in space and time. Highly alkaline cement pore solutions in equilibrium with portlandite (stage II) might exist in certain areas of the near field for very long times. On the other hand, cement degradation may proceed relatively fast to degradation stages III or even IV in parts of the near field where there are: (i) interactions with the host rock; (ii) aggregate-cement reactions and (iii) easily degradable organics. Furthermore, the temporal evolution of cement degradation is controlled by the availability of water and especially the delayed re-saturation of the L/ILW repository (i.e., fully water saturated parts of the repository evolve faster, whereas cement degradation in de-saturated

parts is slowed down). In combination with a complex evolution of water saturation, the heterogeneous distribution of cement materials and waste types in the caverns might result in a strong compartmentalisation of the chemical near field. As a result, a pH domain (i.e., ≥ or < 10.5) has been calculated for each waste package type, based on the MIRAM waste inventory (Nagra 2023b), the amount of CO_2 generated by the degradation rates of organics (Guillemot et al. 2023), and the type of aggregates present in the cement paste (Kosakowski et al. 2020). The pH range for each waste package type is documented in Nagra (2023a).

1.4 Near-field environment in the HLW repository section

The aspects of the phenomenological evolution of the HLW repository near field that are relevant to metal corrosion in the HLW repository are briefly summarised in this section. More details can be found in Nagra (2024c), in prep. and Nagra (2024e), in prep.

For SF canisters, the initial heat output is below 1,500 W per canister. Based on simulations of the current repository concept, temperature at the canister interface with the buffer is expected to reach about 150 °C within about ten years after backfilling and sealing of the drift. During the period until ~ 1,000 years after closure, the canister surface temperature will decline to approximately 80 – 90 °C. In the period from ~ 1,000 to ~ 10,000 years, the buffer temperature will fall from about 80 °C to about 60 °C. Beyond ~ 10,000 years, the temperatures will continue to decrease towards ambient values. For HLW canisters, which have a lower heat loading than the SF canisters, the surface temperature reaches a maximum of around 130 °C a few years after repository closure, followed by a gradual decay.

The results from large scale experiments indicate that gaseous O_2 disappears rapidly after backfilling of the HLW drifts (within weeks). However, an important pool of O_2 may remain stored as sorbed O_2 on the external surfaces of the bentonite. Several processes, such as diffusion of dissolved O_2 towards the OPA, aerobic respiration and corrosion and mineral oxidation, however, will consume the entrapped O_2. In the long-term, anaerobic and reducing conditions will be established throughout the near field within and around the emplacement drifts.

Resaturation of the near field starts after emplacement of the canister and backfilling of the drift with compacted bentonite. A saturation front will develop due to the steep pressure gradient into the high-suction bentonite material which drives vapour diffusion and/or liquid flow, resulting in early saturated conditions near the drift perimeter. A significant period of time will be required for the full saturation of the buffer due to the expected low flow from the OPA, as well as the effects of heat generated by the waste. Saturation of the buffer has been estimated to take around 200 years.

The bentonite blocks and granular bentonite together form a protective mechanical and chemical buffer around the disposal canisters, maintaining near-neutral pH conditions (pH ~ 8).

1.5 Inventory of metallic materials

The types and total amounts of metals and alloys that will be disposed of in the Swiss deep geological repository are fully described in Nagra (2023b). These metallic materials can be linked according to their corrosion properties to form groups of defined corrosion rates as described hereafter.

1.5.1 L/ILW

The complete list of metals and alloys disposed of in the L/ILW repository and the corresponding corrosion groups are provided in Tab. 1-1.

Tab. 1-1: List of metals and alloys to be disposed of in L/ILW caverns and associated corrosion groups[1]

Based on the MIRAM RBG database (Nagra 2023b)

Metals and alloys	Corrosion group
Steel	Iron and carbon steel
Cast iron	Iron and carbon steel
Steel III SIA 162	Iron and carbon steel
CrNi-steel	Stainless steel and Ni alloys
Steel 12.03	Iron and carbon steel
Aluminium Al	Aluminium
Lead Pb	Lead
Steel US A508	Stainless steel and Ni alloys
Steel 37	Iron and carbon steel
Iron Fe	Iron and carbon steel
Steel US 304	Stainless steel and Ni alloys
Stainless steel	Stainless steel and Ni alloys
Copper Cu	Copper
Steel 1.6751	Stainless steel and Ni alloys
Zircaloy-2	Zircaloy
Steel 1.4550	Stainless steel and Ni alloys
Steel 1.4571	Stainless steel and Ni alloys
Steel 1.4301	Stainless steel and Ni alloys
Zircaloy-4	Zircaloy
Nickel Ni	Stainless steel and Ni alloys
Steel 1.6958	Stainless steel and Ni alloys
Zinc Zn	Zinc
Steel 18.8	Stainless steel and Ni alloys
Inconel 600	Stainless steel and Ni alloys
Steel 1.4541	Stainless steel and Ni alloys
PbBi-Eutectic (PbBi55.5%)	Lead
Brass CuZn37%	Zinc
Silver Ag	-
Uranium U	-
Aluminium Al (Mg3%Si1%)	Aluminium
Mild/construction steel	Iron and carbon steel
Halfnium Hf	Zircaloy
Inconel 750	Stainless steel and Ni alloys
Aluminium Al (Mg0.5%Si0.5%)	Aluminium
Tungsten W	Zircaloy

[1] Metals without an assigned corrosion group are metals that are either not expected to corrode under repository conditions or the amounts are negligible compared to the other groups.

Tab. 1-1: Cont.

Metals and alloys	Corrosion group
Tungsten W (Ni6%Cu4%)	Zircaloy
Magnesium Mg	Magnesium
Tin Sn	-
Tantalum Ta	Zircaloy
Nickel Ni (Mo28%)	Stainless steel and Ni alloys
Titanium Ti	Zircaloy
Stellite	Stainless steel and Ni alloys
Gold Au	-
Beryllium Be	-
Thorium Th	-
Inconel 718	Stainless steel and Ni alloys
Cadmium Cd	-
Antimony Sb	-
Zirconium Zr	Zircaloy
Niobium Nb	-
Chromium Cr	Stainless steel and Ni alloys
Calcium Ca	-
Cobalt Co	-

In L/ILW, iron and carbon steel is the largest corrosion group followed by stainless steel and Ni alloys and to a much smaller extent, by aluminium, lead, copper and Zircaloy (Nagra 2023b).

1.5.2 HLW

The complete list of HLW metals and alloys and corresponding corrosion groups are shown in Tab. 1-2.

Tab. 1-2: List of metals and alloys to be disposed of in HLW caverns and associated corrosion groups

Based on the MIRAM RBG database (Nagra 2023b)

Metals disposed of in HLW	Corrosion group
Steel	Iron and carbon steel
Zircaloy-2	Zircaloy
Zircaloy-4	Zircaloy
Stainless steel	Stainless steel and Ni alloys
CrNi-steel	Stainless steel and Ni alloys
Inconel	Stainless steel and Ni alloys
Aluminium Al (Mg3%Si1%)	-
Lead Pb	-

Tab. 1-2: Cont.

Metals disposed of in HLW	Corrosion group
Aluminium Al	-
Copper Cu	-
Brass CuZn37%	-

In HLW, iron and carbon steel is the most predominant corrosion group, primarily due to the disposal canisters (Nagra 2023b). Zircaloy and stainless steel are also present but in smaller amounts compared to iron and carbon steel. The other metals (e.g., aluminium, lead, copper and brass) correspond only to traces[2]. They originate from research reactors and operational activities of the PSI Hot Laboratory (Nagra 2023b).

1.5.3 Construction materials

In the deep geological repository, metals will also be used as construction materials for tunnel support, concrete reinforcement, and shaft lining. Such components will be made almost exclusively from carbon steel[3] and can contribute a significant amount to the total metal inventory in the repository.

[2] As they are present in negligible amounts these metallic materials are not assigned to a corrosion group.

[3] In the current concept, the steel lining of the shaft is foreseen to be stainless steel.

2 Selection of relevant data

2.1 General approach to data selection

A wide range of studies of the corrosion of metallic materials are available in the literature. Most of the available studies supporting deep geological radioactive waste disposal reflect the expected near-field conditions of individual disposal concepts and have been performed according to specific requirements of various national programmes. As a result, a selection of the available data is made in order to consider only results that are representative of, and relevant to, the current Nagra reference concept. However, for some materials the number of available studies is limited. Thus, the selection of relevant studies can become a compromise between the exclusion of irrelevant data and ensuring the inclusion of a wide enough dataset. The criteria used for the selection of relevant corrosion studies are discussed below and in more detail in the following sections of this chapter.

The conditions under which the experiments have been performed are an important factor determining the relevance of a particular corrosion study. Thus, parameters such as the chemistry of the test environment (with focus on the absence of O_2 and the pH) and the temperature are employed as selection criteria. Overall, only corrosion studies performed under anoxic conditions are considered here. In general, the nature of the environment has not been used as a selection criterion, e.g., both tests performed on specimens encased in cementitious grouts and done in simulated cementitious porewater are accepted. Similarly, studies done in both saturated and unsaturated relevant environments are retained in order to cover the expected hydraulic evolution of the repository near field. A particular exception is the selection criteria employed for the SF/HLW disposal canisters, for which only tests in compacted saturated bentonite are accepted.

The corrosion rate of most metallic materials tends to decrease with time due to the gradual build-up of corrosion products on the metal surface and their protective character. A steady-state will prevail when the rate of oxide growth equals the rate of oxide dissolution at the oxide/electrolyte interface. In the relatively benign conditions of the near field of a deep geological repository, it can take a significantly long time until this state is reached. Since the aim of this report is to define corrosion rates that are representative of the long-term evolution of the repository, the test duration is commonly used as a selection criterion. Furthermore, if the same experiment is reported in several publications, only the latest publication containing the longest duration data is considered. Nevertheless, the continuous decline of the corrosion rate even in studies lasting for ~17 years (Hesketh et al. 2023) indicates that the rates reported in the literature, and as a consequence the reference corrosion rates defined in this report, tend to be conservative, since reported experiments last a few years at best.

An additional important factor that was discussed in Diomidis (2014) is the technique used to measure the corrosion rate. It is necessary that the sensitivity of the technique is at least of the same order of magnitude as the measured corrosion rate. Measurements based on the rate of H_2 evolution are generally more sensitive than those based on mass loss or electrochemistry and are preferred for estimating corrosion rates lower than a few 100s nm/a. Tab. 2-1 lists the approximate sensitivities of the H_2 measurement techniques in the studies reviewed for this report.

Tab. 2-1: Sensitivity of different techniques used for measuring evolved H_2 expressed in terms of the corresponding corrosion rate for Fe in units of nm/a

Technique	Solid-state H_2 probe	Pressure transducer	Barometric
Sensitivity	< 0.1 (Senior et al. 2020, Kursten et al. 2021)	~ 1 (Kursten et al. 2021)	~ 100* (Kursten et al. 2021)

* except for the work of Kreis (1993) where 5 nm/a is claimed.

For semi-batch measurements in which gas samples are taken periodically, the precise sensitivity will depend on the sampling interval, with greater sensitivity for longer intervals. Similar to Diomidis (2014), electrochemical methods (i.e., Tafel extrapolation, linear polarisation resistance, impedance techniques) or rates estimated based on the release of ^{14}C from irradiated materials are considered to be unreliable for measurement of the corrosion rate and are excluded from consideration. Furthermore, corrosion rates based only on expert elicitation are excluded.

Some experimental techniques, such as weight loss or batch-type gas generation measurements from sealed ampoules, provide a time-averaged corrosion rate over the duration of the experiment. Here, the focus is on the "instantaneous" corrosion rate at (or close to) the end of the monitoring period, typically determined from the amount of H_2 evolved over a relatively short period of time. In some cases, time-averaged corrosion rates have been converted to an "instantaneous" rate based on the assumption that the rate varies with time (t) according to $t^{-0.5}$. Hesketh et al. (2023) have calculated the time exponent of the power law decay curve of the anaerobic corrosion rate of steel in bentonite in long-term experiments and have found it to range between 0.43 and 0.78, indicating that the employed value of 0.5 is a good approximation.

Generally, no attempt has been made to select data based on a specific alloy composition. Thus, all alloys of a certain corrosion group (cf. Tab. 1-1; Tab. 1-2) are treated as exhibiting the same corrosion behaviour. Similarly, all forms of specimens (e.g., wires, rods, plates) and all starting surface states (e.g., ground, polished, pickled, pre-corroded) are considered, in order to cover, as far as possible, the various forms, shapes and surface states expected to be encountered in the waste.

2.2 Material-specific selection criteria

2.2.1 Iron and carbon steel

The available long-term corrosion studies on iron and carbon steel allow the specification of corrosion rates for both L/ILW and construction materials (under highly alkaline and near-neutral environments) and for the HLW/SF canisters (embedded in bentonite).

Selection criteria for corrosion rates in highly alkaline environments

- pH ≥ 10.5.
- Temperature ≤ 50 °C.
- Experimental duration > 700 days (~ 2 years).
- H_2 measurements with a sensitivity of 5 nm/a or better.

Diomidis (2014) discussed the evidence for the selection of the experimental duration criterion. An additional selection criterion is the measurement sensitivity of 5 nm/a, which is specified because the corrosion rates are low.

Selection criteria for corrosion rates in near-neutral environments

- pH < 10.5.
- Temperature ≤ 50 °C.
- Experimental duration > 365 days (~ 1 year).

A shorter duration criterion compared to bentonite (see below) is employed since there is evidence that steady state is reached faster in solution (King 2008). Since the corrosion rates are higher at the lower pH values representative of an advanced degradation stage of highly alkaline cement or in low-pH cement, mass-loss measurements and all types of H_2 measurements without a sensitivity limitation are accepted for this environment.

Selection criteria for corrosion rates in compacted bentonite

- Compacted saturated bentonite environment.
- Temperature ≤ 80 °C.
- Experimental duration > 1460 days (~ 4 years).

The environment and temperature criteria are selected to represent the conditions to which the SF/HLW disposal canister will be exposed. A relatively long minimum exposure period is specified to ensure, as much as possible, that corrosion rates representative of the long-term canister evolution are retained. Studies carried out in bentonite slurries or in simulated bentonite pore-water solutions are excluded. Since the corrosion rates are relatively high in compacted bentonite, mass-loss measurements and all types of H_2 measurements without a sensitivity limitation are accepted for this environment.

2.2.2 Stainless steel and Ni alloys

The corrosion studies on stainless steel and Ni alloys available in the literature allow the specification of corrosion rates under both highly alkaline and near-neutral environments.

Selection criteria for corrosion rates in highly alkaline environments

- pH ≥ 10.5.
- Temperature ≤ 50 °C.
- Experimental duration > 700 days (~ 2 years).
- H_2 measurements with a sensitivity 2 nm/a or better.

The corrosion rate sensitivity criterion reflects the very low corrosion rates expected for these passive alloys in a deep geological repository environment.

Selection criteria for corrosion rates in near-neutral environments

- pH < 10.5.
- Temperature ≤ 50 °C.
- Experimental duration > 700 days (~ 2 years).
- H_2 measurements with a sensitivity 2 nm/a or better.

2.2.3 Aluminium

The corrosion studies on aluminium available in the literature allow the specification of corrosion rates under both highly alkaline and near-neutral environments.

Selection criteria for corrosion rates in highly alkaline environments

- 10.5 ≤ pH ≤ 13.
- Temperature ≤ 50 °C.
- Experimental duration > 30 days (~ 1 month).

Measurements at pH > 13 are excluded because the corrosion rate of aluminium is very high under these conditions, and it is thus expected to last for only a very short period in the repository.

Selection criteria for corrosion rates in near-neutral environments

- pH < 10.5.
- Temperature ≤ 50 °C.
- Experimental duration > 30 days (~ 1 month).

2.2.4 Lead

Lead is not expected to corrode under anoxic conditions (Pourbaix 1974). However, for completeness, selection criteria were defined for lead corrosion:

- Temperature ≤ 50 °C.

The only relevant study in an anoxic environment was conducted at pH ≥ 10.5. In the absence of data for pH < 10.5, the rates are used for both highly alkaline and near-neutral conditions. Since the corrosion rate of lead increases with increasing pH, the resulting corrosion rates for near-neutral conditions (pH < 10.5) will be conservative.

2.2.5 Zircaloy

The corrosion studies available for Zircaloy allow the specification of corrosion rates for both highly alkaline and near-neutral environments.

Selection criteria for corrosion rates in highly alkaline environments

- pH ≥ 10.5.
- Temperature ≤ 50 °C.
- Experimental duration > 700 days.
- Measurements based only on the generation of H_2.

Because Zr alloys absorb a significant fraction of the H_2 produced by anaerobic corrosion, the corrosion rates are based on the sum of the absorbed and evolved H_2. If only evolved H_2 is reported, the corrosion rate is corrected assuming that 90% of H_2 has been absorbed (Sakuragi 2017a). Kato et al. (2014) analysed the amount of absorbed H_2 after about 70 exposure tests on Zircaloy 2 and 4 and reported H_2 pick-up ratios varying between 34 and 94%, with the vast majority of tests exhibiting pick-up ratios in the 86-94% range.

Selection criteria for corrosion rates in near-neutral environments

Except for the pH, the selection criteria under highly alkaline and near-neutral conditions are identical. The reported rates have also been corrected as discussed above, where necessary. The selection criteria for near-neutral environments are:

- pH < 10.5.
- Temperature ≤ 50 °C.
- Experimental duration > 700 days.
- Measurements based only on the generation of H_2.

2.2.6 Copper

Copper is not expected to corrode under anoxic conditions (Pourbaix 1974). However the vast majority of the studies on the corrosion of copper in a deep geological repository environment have been focused on near-neutral and compacted bentonite environments (Diomidis & King 2022). For completeness, selection criteria were defined for copper corrosion in highly alkaline environments:

- pH ≥ 10.5.
- Temperature ≤ 50 °C.

2.2.7 Zinc

The only available study for Zn in an anoxic environment was conducted at pH ≥ 10.5. In the absence of data for pH < 10.5, the rates are used for both highly alkaline and near-neutral conditions. Since the corrosion rate of zinc increases with increasing pH, the resulting H_2 generation rates in near neutral environments (pH < 10.5) will be conservative.

2.2.8 Magnesium

- 30 °C ≤ temperature ≤50 °C,

The selection criterion related to temperature has been employed because the corrosion rate of magnesium is particularly sensitive to temperature (Cronin & Collier 2012). Based on this criterion, the only available studies are in highly alkaline environment (pH ≥ 10.5). In the absence of data for pH < 10.5, the rates are used for both highly alkaline and near-neutral

conditions. However, the Pourbaix diagram for the Mg-H_2O system suggests that the alloy might passivate due to the formation of a $Mg(OH)_2$ surface film (Pourbaix 1974). Thus, measurements in alkaline environments may not be conservative when applied to near-neutral conditions (pH < 10.5). It should however be noted that any resulting under-estimate of the amount of evolved H_2 is expected to be small as the amount of magnesium in the L/ILW is negligible (Nagra 2023b).

2.3 Corrosion reactions and stoichiometries

For the estimation of the quantity of H_2 evolved for a given amount of corrosion, it is necessary to define the stoichiometry of the corrosion reaction. The following stoichiometric reactions are assumed for the different corrosion groups included in the current review. In almost all cases, the metallic wastes and canister material are alloys containing a principal alloying element (such as Fe in carbon steel and cast iron) plus a number of additional alloying elements (such as Cr in stainless steels and Ni alloys). Here, each alloy group is represented by a single element and a single stochiometric reaction is defined for the calculation of the number of moles of H_2 produced for each mole of corroded metal. Generally, the defined stoichiometry will result in a conservative assessment of the amount of generated H_2.

Iron and carbon steel

The product of the corrosion of iron and carbon steel under anoxic conditions is defined as magnetite Fe_3O_4, formed via the following reaction:

Reaction 2-1: $$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$$

An alternative corrosion product under anoxic conditions is ferrous hydroxide $Fe(OH)_2$, which results in only 1 mole of H_2 per mole of corroded Fe. Hence, the assumption that Fe_3O_4 is the stable corrosion product would result in a conservative prediction of the amount of H_2 produced.

Stainless steel and Ni alloys

Stainless steels and Ni alloys contain a number of elements, including Fe, Ni, and Cr, with Fe as the main constituent of stainless steel and Ni as the main constituent of the Ni alloys. It is assumed that the corrosion product of both stainless steels and Ni alloys is Fe_3O_4 with the same stoichiometry as Reaction 2-1.

This assumption will result in a conservative assessment of H_2 production from the corrosion of the Ni constituent (to form $Ni(OH)_2$) and Fe, if $Fe(OH)_2$ is the stable corrosion product. The amount of H_2 produced by the corrosion of Cr (to form $Cr(OH)_3$) will be underestimated, but this will be balanced by the overestimation of the amount of H_2 produced by the corrosion of Fe and Ni. Overall, it is considered that the assumption of the formation of Fe_3O_4 results in a realistic or slightly conservative assessment.

Aluminium

Based on the Pourbaix diagram for the Al-H_2O system (Pourbaix 1974), the predominant oxidation state for corroded aluminium for the entire range of pH and redox potential of interest is +3. Therefore, the stoichiometry can be represented by:

Reaction 2-2: $2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2$

Lead

Even if lead is not expected to corrode under anoxic conditions (Pourbaix 1974), a finite upper bound corrosion rate was defined. The predominant oxidation state for corroded lead over the pH and redox potential range of interest is +2 (Pourbaix 1974).

The corrosion reaction can be expressed as:

Reaction 2-3: $Pb + H_2O \rightarrow PbO + H_2$

Zircaloy

The predominant oxidation state for zirconium for the pH and redox potential range of interest is +4 (Pourbaix 1974). The corrosion reaction is represented by:

Reaction 2-4: $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$

It is conservatively assumed that 100% of the H_2 produced is evolved and that no H_2 remains either absorbed in the metal or present in the form of zirconium hydride.

Copper

Copper is not expected to corrode under anoxic conditions (Diomidis & King 2022, Pourbaix 1974). However, a finite upper bound corrosion rate is defined for alkaline conditions (see below), for the purposes of which the corrosion product is assumed to be Cu_2O:

Reaction 2-5: $2Cu + H_2O \rightarrow Cu_2O + H_2$

Zinc

Zinc corrodes in the +2 oxidation state over the entire pH and redox potential range of interest (Pourbaix 1974). The corrosion reaction stoichiometry is given by:

Reaction 2-6: $Zn + 2H_2O \rightarrow Zn(OH)_2 + H_2$

Magnesium

Magnesium dissolves in the +2 oxidation state for the pH and redox potentials of interest (Pourbaix 1974). The corrosion reaction can be represented by:

Reaction 2-7: $Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$

3 Corrosion rates

For each corrosion group, values are given for the best estimate corrosion rate, as well as lower and upper bound values.

3.1 Iron and carbon steel

Corrosion rates for iron and carbon steel are defined for anoxic conditions in: (i) highly alkaline environments; (ii) near-neutral environments; and (iii) embedded in compacted bentonite. The reference corrosion rates, including a brief rationale for their selection, for the three above-mentioned environments are shown in Tables 3-1, 3-2 and 3-3, respectively. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.1, which for the three above-mentioned environments are shown in Tables 3-4, 3-5 and 3-6, respectively. The studies excluded from consideration are shown in Tables A-1, A-2 and A-3, respectively.

Tab. 3-1: Overview of reference corrosion rates for iron and carbon steel in anoxic highly alkaline environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	6	Mean of the selected values reported in Tab. 3-4.
Lower bound	3×10^{-2}	Lowest selected value reported in Tab. 3-4 (Senior et al. 2023a).
Upper bound	20	Highest selected value reported in Tab. 3-4 (Kaneko et al. 2004, Nishimura et al. 2003).

Tab. 3-2: Overview of reference corrosion rates for iron and carbon steel in anoxic near-neutral environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	1×10^{3}	Mean of the selected values reported in Tab. 3-5.
Lower bound	0.3	Lowest selected value reported in Tab. 3-5 (Senior & Martino 2022).
Upper bound	7.5×10^{3}	Highest selected value reported in Tab. 3-5 (Xu et al. 2014).

Tab. 3-3: Overview of reference corrosion rates for iron and carbon steel embedded in compacted bentonite

	Corrosion rate (nm/a)	**Rationale**
Best estimate	3×10^2	Mean of the selected values reported in Tab. 3-6.
Lower bound	26	Lowest selected value reported in Tab. 3-6 (Taniguchi et al. 2010).
Upper bound	7×10^2	Highest selected value reported in Tab. 3-6 (Taniguchi et al. 2010).

Tab. 3-4: Selected corrosion studies for iron and carbon steel in anoxic highly alkaline environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
99% Fe	NaOH	12.8	21 ± 3	H_2 (barometric)	~ 700	5	Kreis (1993)
	KOH	12.8				5	
	$Ca(OH)_2$	12.8				2.7	
	Cement pore water Ia	13.2				11	
	Cement pore water Ib	12.9				11	
	Cement pore water II	12.5				2.7	
mild steel	Saturated $Ca(OH)_2$ + 3,000 mg/L Cl^-	12.4	35	H_2 (MS)	900	20	Nishimura et al. (2003)
mild steel	Cement equilibrated water	11.8	30	H_2 (API-MS)	750	5	RWMC (1998); Kaneko et al. (2004)
	Saturated Ca(OH)2 + 5,000 mg/L Cl^-	12.5			892	20	
AISI 1017	YCW + 500 mg/L HS- + 100 mg/L $S_2O_3^{2-}$ irradiated at 25 Gy h^{-1}	13.4	25	H_2 (pressure transducer)	750	8*	Smart et al. (2021)
98% Fe	Portlandite saturated OPA porewater	12.5	50	H_2 (probe)	~ 2,600	3×10^{-2}	Senior et al. (2023a)
	Backfill grout 100% RH	-			~ 2,550	0.5	
						0.3	
		-			~ 2,000	6×10^{-2}	
	Conditioning cement 100% RH	-			~2,000	5×10^{-2}	
	Backfill grout in portlandite sat. OPA porewater	12.5			~ 1,900	9×10^{-2}	
99.5% Fe	Saturated portlandite	12.5			~ 850	0.1	
						8	

* Converted reported average rate to instantaneous rate.

Tab. 3-5: Selected corrosion studies for iron and carbon steel in anoxic near-neutral environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
EN10248-1	Bentonite slurry 30% wt. in artificial groundwater (19,170 ppm Cl^-)	8.1	30	H_2 (barometric)	~ 650	5×10^2	Smart et al. (2004b)
			50			5×10^2	
EN10248-1	Simulated groundwater (32,100 ppm Cl^-)	6.9	50	H_2 (barometric)	856	3.5×10^2	Smart et al. (2004a)
	Buffered groundwater	7			2,607	52	
Q235	Groundwater simulant	7	25	weight loss	365	$7.5\times10^{3*}$	Xu et al. (2014)
98% Fe	100% RH		50	H_2 (probe)	~ 1,800	0.3	Senior & Martino (2022)
99.5% Fe					~ 1,000	10	
98% Fe	Synthetic OPA porewater	8.3			~ 1,800	5×10^2	
EN10248-1	Simulated bentonite porewater	8.4	30	H_2 (barometric)	~ 5,800	1.4×10^2	Unpublished ongoing research
			50		~ 6,600	2.8×10^2	

* Converted reported average rate to instantaneous rate.

Tab. 3-6: Selected corrosion studies for carbon steel embedded in compacted and saturated bentonite under anoxic conditions

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
JIS G3106 SM400B	Saturated with synthetic sea water (19,880 ppm Cl^-)	7.9-8.4	50	weight loss	~ 3,650	$7\times10^{2*}$	Taniguchi et al. (2010)
			80			$3.4\times10^{2*}$	
						$3.3\times10^{2*}$	
	Saturated with high carbonate solution (19,880 ppm Cl^-)	8.3-8.7	80			26^*	
	Saturated with synthetic freshwater (89 ppm Cl^-)	9.1-9.2	80			$4.5\times10^{2*}$	
EN10248-1	Saturated with synthetic OPA porewater	7.2	60	H_2 (barometric)	~ 4,730	2.1×10^2	Unpublished ongoing research
					~ 4,730	1.5×10^2	
					~ 3,130	2.2×10^2	
	Saturated with 1M NaCl	8.4	50		~ 6,550	1.3×10^2	
					~ 4,620	1.1×10^2	
			30		~ 4,680	1.7×10^2	
					~ 1,670	3.6×10^2	
	Saturated with 1M NaCl	11	50		~ 6,530	1.6×10^2	
					~ 4,610	1.2×10^2	
			30		~ 4,670	2.6×10^2	
						2.6×10^2	
	Saturated with 10mM NaCl	8.4	30		~ 6,490	2.2×10^2	
	Saturated with Allard				~ 4,630	3.0×10^2	
						2.3×10^2	
						2.1×10^2	

Tab. 3-6: Cont.

Material	Environment		Temperature	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
ASTM A694-08 F65	Saturated with OPA porewater	7.2	14	weight loss	~ 3,100	$3.3\times10^{2*}$	Unpublished ongoing research
						$3.4\times10^{2*}$	
						$3.3\times10^{2*}$	
						$3.4\times10^{2*}$	
						$3.3\times10^{2*}$	
						$3.7\times10^{2*}$	
						$3.3\times10^{2*}$	
						$3.5\times10^{2*}$	
						$3.1\times10^{2*}$	
						$3.4\times10^{2*}$	
						$3.4\times10^{2*}$	
ASTM A694-08 F65 EB weld						$3.5\times10^{2*}$	
						$3.5\times10^{2*}$	
						$3.6\times10^{2*}$	
						$3.6\times10^{2*}$	
						$3.5\times10^{2*}$	
						$3.3\times10^{2*}$	
						$3.5\times10^{2*}$	
						$3.5\times10^{2*}$	
						$3.3\times10^{2*}$	
ASTM A516 Gr.70						$3.7\times10^{2*}$	
						$4.3\times10^{2*}$	
						$3.7\times10^{2*}$	
						$3.6\times10^{2*}$	
						$3.3\times10^{2*}$	
						$3.4\times10^{2*}$	

* Converted reported average rate to instantaneous rate.

3.2 Stainless steel and Ni alloys

Corrosion rates for stainless steel and Ni alloys are defined for both highly alkaline and near-neutral anoxic environments. The reference corrosion rates, including a brief rationale for their selection, for the above-mentioned environments are shown in Tables 3-7 and 3-8, respectively. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.2, which for the above-mentioned environments are shown in Tables 3-9 and 3-10, respectively. The studies excluded from consideration are shown in Tables A-4 and A-5.

Tab. 3-7: Overview of reference corrosion rates for stainless steel and Ni alloys in anoxic highly alkaline environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	0.6	Mean of the selected values reported in Tab. 3-9.
Lower bound	2×10^{-2}	Lowest selected value reported in Tab. 3-9 (Senior et al. 2023b).
Upper bound	1.4	Highest selected value reported in Tab. 3-9 (Sakuragi et al. 2016b).

Tab. 3-8: Overview of reference corrosion rates for stainless steel and Ni alloys in anoxic near-neutral environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	0.4	Mean of the selected values reported in Tab. 3-10.
Lower bound	0.2	Lowest selected value reported in Tab. 3-10 (Sakuragi 2017b).
Upper bound	1	Highest selected value reported in Tab. 3-10 (Sakuragi 2017b).

Tab. 3-9: Selected corrosion studies for stainless steel and nickel alloys in anoxic highly alkaline environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
18Cr-8Ni austenitic SS	NaOH	12.5	30	H_2 (API-MS) – gas flow	2,360	0.36	Sakuragi et al. (2016a)
						0.39	
18Cr-8Ni austenitic SS	NaOH	12.5	30	H_2 (GC) – ampoule tests	720	0.32*	Sakuragi et al. (2016b)
						0.46*	
			50			1.2*	
						1.4*	
Unknown (1.4541 or 1.4550 or 1.4571)	ACW	12.5	25	H_2 (GC-MS)	1,637	1	Guillemot et al. (2022)
316L	Encased in CEM I at 100% RH	-	50	H_2 (probe)	~ 1,300	0.2	Senior et al. (2023c)
	Encased in CEM I immersed in YCW	13.5				< 2×10^{-2}**	

* Converted reported average rate to instantaneous rate.

** Below detection limit.

Tab. 3-10: Selected corrosion studies for stainless steel and nickel alloys in anoxic near-neutral environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
18Cr-8Ni austenitic SS	deionised water	-	25	H_2 (API-MS) - gas flow	~ 1,000	0.2	Sakuragi (2017b)
					~ 900	0.3	
			30	H_2 (GC-TCD) – ampoule tests	~ 1,095	0.25*	
			50			1*	

* Converted the reported average rate to instantaneous rate.

3.3 Aluminium

Corrosion rates for aluminium are defined for both highly alkaline and near-neutral anoxic environments. The reference corrosion rates, including a brief rationale for their selection, for the above-mentioned environments are shown in Tab. 3-11 and 3-12, respectively. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.3, which for the above-mentioned environments are shown in Tables 3-13 and 3-14, respectively. The studies excluded from consideration are shown in Table A-6.

Tab. 3-11: Overview of reference corrosion rates for aluminium in anoxic highly alkaline environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	6.4×10^{4}	Mean of the selected values reported in Tab. 3-13.
Lower bound	10	Lowest selected value reported in Tab. 3-13 (Mendibide et al. 2021).
Upper bound	3×10^{5}	Highest selected value reported in Tab. 3-13 (Mendibide et al. 2021).

Tab. 3-12: Overview of reference corrosion rates for aluminium in anoxic near-neutral environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	7×10^{3}	Only reported value in Tab. 3.14.
Lower bound		
Upper bound		

Tab. 3-13: Selected corrosion studies for aluminium in anoxic highly alkaline environments*

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
JIS A 1070	OPC equilibrated solution	12.6	15	H_2 (GC)	~ 200	5×10^3	Fujisawa et al. (1996)
	In pulverised OPC mortar				~ 200	8×10^2	
	Encased in OPC mortar				~ 175	8×10^2	
JIS A 1070P	OPC equilibrated solution	11.9-12.8	15	H_2 (GC)	333	1×10^3	Fujiwara et al. (2017)
EN-AW-5754	Portlandite buffered porewater	12.2	25	H_2 (volumetric counter)	30	3×10^5	Mendibide et al. (2021)
				weight loss		$2\times10^{5*}$	
						$2\times10^{5*}$	
	CEM I grout during curing	12.5		weight loss	120	$8\times10^{4*}$	
	CEM III/C grout during curing	11.5				$1\times10^{4*}$	
	Encased in CEM I grout at 95-97% RH	12.5		H_2 (GC)	~ 380	6.5×10^2	
	Encased in CEM III/C grout at 95-97% RH	11.5				$< 10^{**}$	
99.99% Al	Saturated portlandite	12.5	50	H_2 (pressure transducer)	~ 900	2×10^3	Senior et al. (2023b)
AA2024					~ 185	3×10^4	

* Reported average corrosion rates have not been corrected since the temporal evolution of the corrosion rate does not always follow $t^{-0.5}$.

** Below detection limit.

Tab. 3-14: Selected corrosion studies for aluminium in anoxic near-neutral environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
AA2024	Groundwater simulant	7	25	weight loss	365	$7\times10^{3*}$	Xu et al. (2014)

* Reported average corrosion rates have not been corrected since the temporal evolution of the corrosion rate does not always follow $t^{-0.5}$.

3.4 Lead

Corrosion rates for lead are defined for anoxic environments and, including a brief rationale for their selection, are shown in Table 3-15. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.4, which are shown in Tab. 3-16. The studies excluded from consideration are listed in Table A-7.

Tab. 3-15: Overview of reference corrosion rates for lead in anoxic highly alkaline and near-neutral environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	0	Expected thermodynamic stability in anoxic conditions.
Lower bound	0	
Upper bound	0.5	Highest selected value in Tab. 3-16 (Senior et al. 2023b).

Tab. 3-16: Selected corrosion studies for lead under anoxic highly alkaline environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
99.99% Pb wire	Saturated portlandite	12.5	50	H_2 (probe)	~ 730	0.5	Senior et al. (2023b)
	YCW	13.5				0.3	

3.5 Zircaloy

Corrosion rates for Zircaloy are defined for both highly alkaline and near-neutral anoxic environments. The reference corrosion rates, including a brief rationale for their selection, for the above-mentioned environments are shown in Tables 3-17 and 3-18, respectively. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.5, which for the above-mentioned environments are shown in Tables 3-19 and 3-20, respectively. The studies excluded from consideration are shown in Tables A-8 and A-9.

Tab. 3-17: Overview of reference corrosion rates for Zircaloy in anoxic highly alkaline environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	3	Average selected value reported in Tab. 3-19.
Lower bound	0.4	Lowest selected value reported in Tab. 3-19 (Senior et al. 2023b).
Upper bound	9	Highest selected value reported in Tab. 3-19 (Sakuragi et al. 2013).

Tab. 3-18: Overview of reference corrosion rates for Zircaloy in anoxic near-neutral environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	2.3	Average of the selected values reported in Tab. 3-20 (Sakuragi 2017a).
Lower bound	1.5	Lowest of the selected values reported in Tab. 3-20 (Sakuragi 2017a).
Upper bound	3	Highest selected value reported in Tab. 3-20 (Sakuragi 2017a).

Tab. 3-19: Selected corrosion studies for Zircaloy in anoxic highly alkaline environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
Zircaloy-4	NaOH	12.5	30	H_2 (API-MS and gas flow)	1,500	5.7	Sakuragi et al. (2013)
						5.8	
Zircaloy-2					1,000	8.8	
Zircaloy-4	NaOH	12.5	30	H_2 (GC) – ampoule tests	730	1.9*	Kato et al. (2014)
						1.8*	
			50		1,825	1.7*	
						1.5*	
Zircaloy-2	NaOH	12.5	30	H_2 (GC) – ampoule tests	730	1.9*	
						2.3*	
			50		730	3.2*	
						3.3*	
Zircaloy-4	NaOH	12.5	50	H_2 (GC-TCD) – ampoule tests	~ 730	3*	Sakuragi (2017a)
99.2% Zr wire	Saturated portlandite	12.5	50	H_2 (probe)	~ 730	0.4**	Senior et al. (2023b)
	YCW	13.5				0.7**	

* Converted reported average rate to instantaneous rate.

** Corrected for H_2 adsorption.

Tab. 3-20: Selected corrosion studies for Zircaloy in anoxic near-neutral environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
Pure Zr	Deionised water	-	50	H_2 (GC-TCD) - ampoule tests	~ 730	3.0*	Sakuragi (2017a)
			30			1.5*	

* Converted reported average rate to instantaneous rate.

3.6 Copper

Corrosion rates for copper are defined for anoxic highly alkaline environments and, including a brief rationale for their selection, are shown in Table 3-21. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.6, which are shown in Tab. 3-22. For near-neutral pH conditions (pH < 10.5), the overwhelming evidence is that copper does not corrode in O_2-free environments (Diomidis and King 2022). Therefore, for these conditions, the best estimate and lower and upper bound corrosion rates are all defined as zero. No studies in highly alkaline conditions were excluded from consideration.

Tab. 3-21: Overview of reference corrosion rates for copper in anoxic highly alkaline environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	0	Based on the absence of complexing species such as sulphides that support H_2 evolution.
Lower bound	0	
Upper bound	5×10^{-2}	Based on the highest selected value reported in Tab. 3-22 (Senior et al. 2023b).

Tab. 3-22: Selected corrosion studies for copper in anoxic highly alkaline environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
99.9% Cu wire	YCW	13.5	50	H_2 (probe)	~ 730	5×10^{-2}	Senior et al. (2023b)
	Saturated portlandite	12.5				$< 5\times10^{-3}$*	

* Below detection limit.

3.7 Zinc

Corrosion rates for zinc are defined for anoxic environments and, including a brief rationale for their selection, are shown in Table 3-23. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.7, which are shown in Tab. 3-16. No studies are excluded from consideration.

Tab. 3-23: Overview of reference corrosion rates for zinc in anoxic highly alkaline environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	1.5×10^{2}	Average selected value reported in Tab. 3-24.
Lower bound	90	Lowest selected value reported in Tab. 3-24 (Senior et al. 2023b).
Upper bound	2×10^{2}	Highest selected value reported in Tab. 3-24 (Senior et al. 2023b).

Tab. 3-24: Selected corrosion studies for zinc in anoxic environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
99.99% Zn wire	Saturated portlandite	12.5	50	H_2 (pressure transducer)	~ 900	2×10^2	Senior et al. (2023b)
	YCW	13.5				90	

3.8 Magnesium

Corrosion rates for magnesium are defined for anoxic environments and, including a brief rationale for their selection, are shown in Table 3-25. The reference rates were defined based on the studies retained according to the selection criteria described in Section 2.2.8, which are shown in Tab. 3-26. The studies excluded from consideration are shown in Table A-10.

Tab. 3-25: Overview of reference corrosion rates for magnesium in anoxic highly alkaline environments

	Corrosion rate (nm/a)	**Rationale**
Best estimate	7.6×10^{3}	Average selected value reported in Tab. 3-26.
Lower bound	8×10^{2}	Lowest selected value reported in Tab. 3-26 (Cronin & Collier 2012).
Upper bound	2×10^{4}	Highest selected value reported in Tab. 3-26 (Senior et al. 2023b).

Tab. 3-26: Selected corrosion studies for magnesium in anoxic environments

Material	Environment		Temperature (°C)	Measurement technique	Test duration (days)	Corrosion rate (nm/a)	Reference
	Type	pH					
Magnox swarf (0.7-0.9% Al)	OPC/BFS grout		40	H_2 (pressure transducer)	~ 900	8×10^2	Cronin & Collier (2012)
						1.6×10^3	
99.9% Mg rods	YCW	13.5	50	H_2 (pressure transducer)	~ 550	2×10^4	Senior et al. (2023b)
	Saturated portlandite	12.5				8×10^3	

4 Summary

The available literature on the corrosion of metallic materials to be disposed of in a Swiss deep geological repository has been reviewed with the aim of defining reference corrosion rates to be used in performance and safety assessments. Compared to the last such review done 10 years ago significantly more experimental data and improved understanding of mechanisms and processes are now available. The newly available experimental data formed the basis for the definition of reference rates for all corrosion groups, avoiding the need for expert judgement. The improved understanding of relevant processes allowed a refinement of the criteria used for the selection of studies that are representative of the near-field conditions expected for the Swiss disposal concept. The new selection criteria led to the definition of pH-dependent corrosion rates for more materials, and the avoidance of overconservative and less relevant corrosion studies. A summary of the defined corrosion rates is shown in Tab. 4-1.

Tab. 4-1: Reference corrosion rates for metallic materials predominantly present in the Swiss waste inventory

Materials	**Environment**	**Lower bound**	**Best estimate**	**Upper bound**
		(nm/a)		
Iron and carbon steel	pH ≥ 10.5	3×10^{-2}	6	20
	pH < 10.5	0.3	1×10^{3}	7.5×10^{3}
	Compacted bentonite	26	3×10^{2}	7×10^{2}
Stainless steel and Ni alloys	pH ≥ 10.5	2×10^{-2}	0.6	1.4
	pH < 10.5	0.2	0.4	1
Aluminium	pH ≥ 10.5	10	6.4×10^{4}	3×10^{5}
	pH < 10.5	7×10^{3}	7×10^{3}	7×10^{3}
Lead	pH ≥ 10.5	0	0	0.5
	pH < 10.5			
Zircaloy	pH ≥ 10.5	0.4	3	9
	pH < 10.5	1.5	2.3	3
Copper	pH ≥ 10.5	0	0	5×10^{-2}
	pH < 10.5	0	0	0
Zinc	pH ≥ 10.5	90	1.5×10^{2}	2×10^{2}
	pH < 10.5			
Magnesium	pH ≥ 10.5	8×10^{2}	7.6×10^{3}	2×10^{4}
	pH < 10.5			

5 References

Andra (2013): Référentiel du comportement des colis de déchets HA-MAVL. Tome 3. Déchets MAVL. CG.RP.ASCM.12.0026. Andra, Châtenay-Malabry, France.

Andrade, C. & Page, C.L. (1986): Pore solution chemistry in hydrated cement systems containing chloride salts: A study of cation specific effects. British Corrosion Journal 21, 49-54. DOI: 10.1179/000705986798272415.

Arup, H. (1983): The mechanisms of the protection of steel by concrete. *In:* Crane, A. (ed.): Corrosion of reinforcement in concrete construction: Ellis Horwood Ltd. Chichester, West Essex, UK, 151-157.

Azizi, O., Chen, Y. & Macdonald, D.D. (2008): Characterisation of the passive film on carbon steel in saturated Ca(OH)2+NaOH solution. NIRAS/ONDRAF report, Pennsylvania State University, USA.

Bucur, C., Fulger, M., Florea, I., Dobrin, R., Diaconescu, C., Tudose, A. & Uta, O. (2017): CAST: Final report on experimental results on long-term corrosion tests and C14 release assessment, irradiated Zircaloy. (RATEN-ICN). CAST-2017-D3.16 Euratom 7th Framework Programme Project. European Comission.

Caes, S., Druyts, F. & Thomas, P. (2018): Release and speciation of carbon from Zircaloy-4 in anaerobic and highly alkaline conditions: Comparison of simple immersion and potentiostatic corrosion tests. Radiocarbon 60, 1787-1796. DOI: 10.1017/RDC.2018.105.

Caes, S., Gurning, A.C., Li, X., Souza, V. de & Kursten, B. (2022): Corrosion of aluminium in ordinary Portland cement paste: Influence of matrix porosity and the presence of LiNO3 corrosion inhibitor. Materials and Corrosion 74, 125-137. DOI: 10.1002/maco.202213296.

Chomat, L., Amblard, E., Varlet, J., Blanc, C. & Bourbon, X. (2017): Passive corrosion of steel reinforcement in blended cement-based material in the context of nuclear waste disposal. Corrosion Engineering, Science and Technology 52/sup1, 148-154. DOI: 10.1080/1478422X.2017.1300378.

Chomat, L., L'Hostis, V., Amblard, E. & Bellot-Gurlet, L. (2014): Long term study of passive corrosion of steel rebars in Portland mortar in context of nuclear waste disposal. Corrosion Engineering, Science and Technology 49, 467-472. DOI: 10.1179/1743278214Y.0000000201.

Cronin, J. & Collier, N. (2012): Corrosion and expansion of grouted Magnox. Mineralogical Magazine 76/8, 2901-2909. DOI: 10.1180/minmag.2012.076.8.05.

Diomidis, N. (2014): Scientific basis for the production of gas due to corrosion in a deep geological repository. Nagra Work Report NAB 14-21.

Diomidis, N. & King, F. (2022): Development of Copper Coated Canisters for the Disposal of SF and HLW in Switzerland. Nagra Technical Report NTB 20-01.

Dobrev, D., Stammose, D., Pelligrini, D. & Vokal, A. (2013): FORGE Work Package 2 final report - Experimental studies on hydrogen generation by corrosion. Forge-2013-D2.5-R Euratom 7th Framework Programme Project. European Comission.

Duffó, G.S., Farina, S.B. & Schulz, F.M. (2013): Corrosion of steel drums containing cemented ion-exchange resins as intermediate level nuclear waste. Journal of Nuclear Materials 438, 116-125. DOI: 10.1016/j.jnucmat.2013.03.027.

Federation of Electric Power Companies of Japan and Japan Atomic Energy Agency (2007): Second progress report on research and development for TRU waste disposal in Japan. JAEA-Review 2007-010/ FEPC TRU-TR2-2007-01. JAEA, Tokyo, Japan.

Fraker, A.C. & Harris, J.S. (1990): Corrosion behavior of zirconium alloy nuclear fuel cladding. MRS Online Proceedings Library 176, 549-556. DOI: 10.1557/PROC-176-549.

Fujisawa, R., Cho, T., Sugahara, K., Takizawa, Y., Horikawa, Y., Shiomi, T. & Hironaga, M. (1996): The corrosion behavior of iron and aluminum under waste disposal conditions. MRS Online Proceedings Library 465, 675-682. DOI: 10.1557/PROC-465-675.

Fujisawa, R., Kurashige T., Inagaki, Y. & Senoo, M. (1999): Gas generation of transuranic waste under disposal conditions. MRS Online Proceedings Library 556, 1199-1206. DOI: 10.1557/PROC-556-1199.

Fujiwara, A. (2002): Gas generation by steel corrosion under reductive conditions - Continous measurement test. GASNET Workshop, Cologne, Germany (2002).

Fujiwara, A., Yasutomi, I., Fukudome, K., Tateishi, T. & Fujiwara, K. (2000): Influence of oxygen concentration and alkalinity on the hydrogen gas generation by corrosion of carbon steel. MRS Online Proceedings Library 663, 497-505. DOI: 10.1557/PROC-663-497.

Fujiwara, K., Tani, J., Hironaga, M. & Tanaka, Y. (2017): Corrosion behaviour of aluminium under simulated environmental conditions of low-level waste. Corrosion Engineering, Science and Technology 52/sup1, 162-165. DOI: 10.1080/1478422X.2017.1306390.

González, J.A., Algaba, S. & Andrade, C. (1980): Corrosion of reinforcing bars in carbonated concrete. British Corrosion Journal 15/3, 135-139. DOI: 10.1179/bcj.1980.15.3.135.

Goodwin, F.E. & Guenther, R.J. (1987): Corrosion of lead and lead alloys in simulated repository environments. MRS Online Proceedings Library 112, 783-792. DOI: 10.1557/PROC-112-783.

Grauer, R. (1988): The corrosion behaviour of carbon steel in Portland cement. Nagra Technical Report NTB 88-02 E.

Grauer, R., Knecht, B., Kreis, P. & Simpson, J.P. (1990): Hydrogen evolution from corrosion of iron and steel in intermediate level waste repositories. MRS Online Proceedings Library 212, 295-302. DOI: 10.1557/PROC-212-295.

Grauer, R., Knecht, B., Kreis, P. & Simpson, J.P. (1991): The long term corrosion rate of passive iron in anaerobic alkaline solutions. Materials and Corrosion 42/12, 637-642. DOI: 10.1002/MACO.19910421205.

Grubitsch, H., Binder, L. & Hilbert, F. (1979): The influence of various concentrations of chloride ions on the active-passive corrosion susceptibility of steel in saturated calcium hydroxide solution. Materials and Corrosion 30/4, 241-245. DOI: 10.1002/maco.19790300403.

Grubitsch, H., Miklautz H. & Hilbert, F. (1970): Potentiodynamische und potentiostatische Messungen an gespannten Drahtelektroden in gesättigten Ca(OH)2-Lösungen mit verschiedenen Zusätzen. Werkstoffe und Korrosion 21/6, 485-495. DOI: 10.1002/maco.19700210608.

Guillemot, T., Salazar, G., Rauber, M., Kunz, D., Szidat, S. & Wieland, E. (2022): Carbon-14 release and speciation during corrosion of irradiated steel under radioactive waste disposal conditions. Science of the Total Environment 817. DOI: 10.1016/j.scitotenv.2021.152596.

Guillemot, T., Wieland, E., Mosberger, L. & Warthmann, R. (2023): Degradation of organic materials in the context of a L/ILW repository. Nagra Technical Report NTB 23-11.

Hansson, C.M. (1984): The corrosion of zircaloy-2 in anaerobic synthetic cement pore solution. SKB TR 84-13. SKB, Stockholm, Sweden.

Hansson, C.M. (1985a): Hydrogen evolution in anaerobic concrete resulting from corrosion of steel reinforcement. Teknisk PM 30. SKB, Stockholm, Sweden.

Hansson, C.M. (1985b): The Corrosion of Steel and Zirconium in Anaerobic Concrete. MRS Online Proceedings Library 50, 475-482. DOI: 10.1557/PROC-50-475.

Hansson, C.M. (1985c): The corrosion rate of mild steel in deaerated synthetic cement pore solution. Teknisk PM 29. SKB, Stockholm, Sweden.

Hansson, C.M. (1987): The corrosion of steel in anaerobic concrete and the associated evolution of hydrogen. SFR-87-02. SKB, Stockholm, Sweden.

He, X. & Ahn, T. (2015): Carbon Steel Corrosion in Anoxic Alkaline Solution. NACE-2015-5571. NACE - International Corrosion Conference Series, Dallas, Texas, USA (15.03.2015).

He, X., Ahn, T. & Gwo, J.P. (2017): Carbon steel corrosion in simulated anoxic concrete pore water for nuclear waste disposal application. Corrosion 73/11, 1381-1393. DOI: 10.5006/2430.

Hélie, M. (2004): Dossier de synthèse sur le comportement à long terme des colis: dossier de référence phénoménologique CSD-C 2004. RT DPC/SCCME 04-685-A. CEA, Gif Sur Yvette, France.

Hesketh, J., Haynes, H., Reddy, B., Rance, A., Bevas, C., Padovani, C. & Diomidis, N. (2023): Carbon steel corrosion in a bentonite buffer: A comparison between in-situ exposure and lab-based experiment. Materials and Corrosion/in press. DOI: 10.1002/maco.202313767.

Heusler, K.E., Weil, K.G. & Bonhoeffer, K.F. (1958): Die Bedeutung des Flade-Potentials für die Passivität des Eisens in alkalischen Lösungen. Zeitschrift für Physikalische Chemie 15, 149-161. DOI: 10.1524/ZPCH.1958.15.1-6.149.

Hillner, E. (1977): Corrosion of zirconium-base alloys: An overview. 3rd Int. Symp. ASTM STP Zirconium in the nuclear industry 633/633, 211-235. DOI: 10.1520/STP35573S.

Honda, A., Kato, T., Tateishi, T., Imakita, T., Masuda, K., Kato, O. & Nishimura, T. (2006): Chemical transition of nitrate ions accompagnied by corrosion of carbon steel under alkaline conditions. Zairyo To Kankyo 55/10, 458-465. DOI: 10.3323/jcorr.55.458.

Honda, A., Masuda, K., Imakita, T., Kato, O. & Nishimura, T. (2009): Modelling of chemical transition of nitrate accompanied by corrosion of carbon steel under alkaline conditions. Zairyo To Kankyo 58/5, 182-189. DOI: 10.3323/jcorr.58.182.

IAEA (1998): Waterside corrosion of zirconium alloys in nuclear power plants. IAEA-TECDOC-996 KAERI/AR-547/99. IAEA, Vienna, Austria.

IAEA (2006): Understanding and Managing Ageing of Material in Spent Fuel Storage Facilities. IAEA Technical Reports Series 443. IAEA, Vienna, Austria.

Jelinek, J. & Neufeld, P. (1982): Kinetics of Hydrogen Formation from Mild Steel in Water under Anaerobic Conditions. Corrosion 38/2, 98-104. DOI: 10.5006/1.3577332.

JNC (2000): H12: Project to establish the scientific and technical basis fro HLW disposal in Japan. Supporting report 2: Repository design and engineering technology. JNC TN1410, 2000-003. Japan Nuclear Cycle Development Institute, Ibaraki, Japan.

Johnson, A.B. (1977): Behavior of spent nuclear fuel in water pool storage. Technical report BNWL-2256 UC70. PNL, Richland, WA, USA.

Johnson, L. & McGinnes, D.F. (2002): Partitioning of Radionuclides in Swiss Power Reactor Fuels. Nagra Technical Report NTB 02-07.

Jung, H., Ahn, T. & He, X. (Aprill 10-14 2011): Representation of copper and carbon steel waste package container degradation in a generic performance assessment model. 13th International High-Level Radioactive Waste Management Conference (Aprill 10-14 2011).

Kaesche, H. (1965): Untersuchungen über die Korrosion unlegierter Stähle in Kalziumhydroxydlösung und in feuchtem Beton. Archiv für das Eisenhüttenwesen 36/12, 911-922. DOI: 10.1002/SRIN.196502724.

Kaneko, M., Miura, N., Fujiwara, A. & Yamamoto, M. (2004): Evaluation of gas generation rate by metal corrosion in the reducing environment. Report RWMC-TRE-03003. RWMC, Tokyo, Japan.

Kato, O., Tanabe, H., Sakuragi, T., Nishimura, T. & Tateishi, T. (2014): Corrosion Tests of Zircaloy Hull Waste to Confirm Applicability of Corrosion Model and to Evaluate Influence Factors on Corrosion Rate under Geological Disposal Conditions. MRS Online Proceedings Library 1665, 195-202. DOI: 10.1557/opl.2014.646.

King, F. (2008): Corrosion of carbon steel under anaerobic conditions in a repository for SF and HLW in Opalinus Clay. Nagra Technical Report NTB 08-12.

Kogawa, N. (2003): Migration of C-14 in activated metal under anaerobic alkaline conditions. In: Proceedings of Nagra/RWMC Workshop on the release and transport of C14 in repository environments. Nagra Work Report NAB 08-22.

Kosakowski, G., Huang, Y. & Wieland, E. (2020): Influence of material heterogeneities, process couplings and aggregate reactivity on the geochemical evolution of the L/ILW repository. Nagra Work Report NAB 20-11.

Kreis, P. (1991): Hydrogen Evolution from corrosion of iron and steel in low/intermediate level waste repositories. Nagra Technical Report NTB 91-21.

Kreis, P. (1993): Wasserstoffentwicklung durch Korrosion von Eisen und Stahl in anaeroben, alkalischen Medien im Hinblick auf ein SMA-Endlager. Nagra Technischer Bericht NTB 93-27.

Kreis, P. & Simpson, J.P. (1992): Hydrogen gas generation from the corrosion of iron in cementitious environments. (EFC Publication 7, A working report on corrosion problems related to nuclear waste disposal). Institute of Materials, London, UK.

Kurashige, T., Fujisawa, R., Inagaki, Y. & Senoo, M. (1999): Gas generation behavior of Zircaloy-4 under waste disposal conditions. ASME (1999).

Kursten, B., Druyts, F., Macdonald, D.D., Smart, N.R., Gens, R., Wang, L., Weetjens, E. & Govaerts, J. (2011): Review of corrosion studies of metallic barrier in geological disposal conditions with respect to Belgian Supercontainer concept. Corrosion Engineering, Science and Technology 46/2, 91-97. DOI: 10.1179/1743278210Y.0000000022.

Kursten, B., Druyts, F., Smart, N.R., Macdonald, D.D., Gens, R., Wang, L., Weetjens, E. & Govaerts, J. (2013): Review of passive corrosion studies of carbon steel in concrete in the context of disposal of HLW and spent fuel in Belgium. Proceedings of the ASME 2013 15th International Conference on Environmental Remediation and Radioactive Waste Management, Brussels, Belgium (2013).

Kursten, B., Macdonald, D.D., Smart, N.R. & Gaggiano, R. (2017): Corrosion issues of carbon steel radioactive waste packages exposed to cementitious materials with respect to the Belgian supercontainer concept. Corrosion Engineering, Science and Technology 52/sup1, 11-16. DOI: 10.1080/1478422X.2017.1292345.

Kursten, B., Smart, N.R., Senior, N., Macdonald, D.D., Caes, S., Souza, V. de & Gaggiano, R. (2021): Overview of anaerobic corrosion of carbon steel radioactive waste packages in alkaline media in support of the Belgian supercontainer concept. Materials and Corrosion 72, 32-51. DOI: 10.1002/maco.202011794.

Landolt, D. (2007): Corrosion and Surface Chemistry of Metals. 1st Edition. EPFL Press, New York, USA.

Lee, D.J. & Wilding, C.R. (1989): The corrosion of aluminium in cement - A review of the current position. CPDG(89)P263.

L'Hostis, V., Amblard, E., Blanc, C., Miserque, F., Paris, C. & Bellot-Gurlet, L. (2011): Passive corrosion of steel in concrete in context of nuclear waste disposal. Corrosion Engineering, Science and Technology 46, 177-181. DOI: 10.1179/1743278210Y.0000000013.

Macdonald, D.D. (2006): Impact of radiolysis on the corrosion potential. Corrosion Expert Panel Meeting. NIRAS/ONDRAF, Brussels, Belgium (2006).

Macdonald, D.D. & Azizi, O. (2008): Characterisation of the passive film on carbon steel in saturated Ca(OH)2+NaOH solution at 60C. 6th JRT Meeting, Brussels, Belgium (2008).

Macdonald, D.D., Azizi, O. & Saleh, A. (2009a): Characterisation of the passive film on carbon steel in saturated Ca(OH)2+NaOH solution as a function of temperature. 7th JRT Meeting, Cadarache, France (2009).

Macdonald, D.D., Azizi, O. & Saleh, A. (2009b): The electrochemistry of carbon steel in simulated concrete pore water. 8th JRT Meeting, Brussels, Belgium (2009).

Macdonald, D.D., Chen, Y. & Nicic, I. (2007): The electrochemistry of carbon steel in saturated Ca(OH)2 solution. NIRAS/ONDRAF, Pennsylvania State University, USA (2007).

Macdonald, D.D., Engelhardt, G.R., Urquidi-Macdonald, M., Saleh, A., Lee, S.-K., Sharifi-Asl, S., Rosas, O., Almarzooqi, A. & Taylor, M. (2010a): The electrochemistry of carbon steel in simulated concrete pore water. 10th JRT Meeting, Brussels, Belgium (2010).

Macdonald, D.D., Saleh, A., Almarzooqi, A. & Rosas, O. (2010b): Corrosion of carbon steel in simulated concrete pore water. 9th JRT Meeting, Brussels, Belgium (2010).

Marsh, G.P. & Taylor, K.J. (1988): An assessment of carbon steel containers for radioactive waste disposal. Corrosion Science 28/3, 289-320. DOI: 10.1016/0010-938X(88)90111-4.

Matsuda, F., Wada, R., Fujiwara, K. & Fujiwara, A. (1994): An Evaluation of Hydrogen Evolution from Corrosion of Carbon Steel in Low/Intermediate Level Waste Repositories. MRS Online Proceedings Library 353, 719-726. DOI: 10.1557/PROC-353-719.

Mendibide, C., Dusquesnes, V., Deydier, V., Bourbon, X. & Crusset, D. (2021): Corrosion behavior of aluminium alloy 5754 in cement-based matrix-simulating nuclear waste disposal conditions. Materials and Corrosion 71/1-2, 383-395. DOI: 10.1002/maco.202011687.

Mihara, M., Honda, A., Nishimura, T. & Wada, R. (2002): Estimation on gas generation and corrosion rates of carbon steel, stainless steel and zircaloy in alkaline solutions under low oxygen condition. JNC Technical review 15, 91-101.

Nagra (2021): Waste management programme 2021 of the waste producers. Nagra Technical Report NTB 21-01E.

Nagra (2023a): Chemical Criteria for Waste Group Classification: a Model Approach. Nagra Work Report NAB 23-28.

Nagra (2023b): Modellhaftes Inventar für radioaktive Materialien MIRAM-RBG. Nagra Technischer Bericht NTB 22-05.

Nagra (2024a, in prep.): Consequence analysis for SGT E3. Nagra Technical Report NTB 24-18.

Nagra (2024b, in prep.): Design and performance assessment of SF/HLW disposal canisters for RBG. Nagra Technical Report NTB 24-20.

Nagra (2024c, in prep.): Geochemical Evolution of the HLW Near-Field. Nagra Technical Report NTB 23-02.

Nagra (2024d, in prep.): Geochemical Evolution of the L/ILW Near-Field. Nagra Technical Report NTB 23-03.

Nagra (2024e, in prep.): Phenomenological description of the evolution of a combined geological repository for radioactive waste at Nördlich Lägern in Opalinus Clay. Nagra Work Report NAB 24-20.

Nagra (2024f, in prep.): Production, consumption and transport of gases in a deep geological repository for combined disposal in Switzerland. Nagra Technical Report NTB 24-23.

Nagra (2024g, in prep.): Treatment of C-14 treatment in the post-closure safety assessments. Nagra Work Report NAB 24-07.

Naish, C.C. (1993): Corrosion aspects of the proposed Sellafield waste repository. The NACE Annual Conference and Corrosion Show (1993).

Naish, C.C., Balkwill, P.H., O'Brien, T.M., Taylor, K.J. & Marsh, G.P. (1990): The anaerobic corrosion of carbon steel in concrete. Report NSS-R-273. AEA Technology, Harwell, UK.

Naish, C.C., Balkwill, P.H., O'Brien, T.M., Taylor, K.J. & Marsh, G.P. (1991): The anaerobic corrosion of carbon steel in concrete. Report EUR-13663 EN. Commission of the European Communities, Luxembourg.

Naish, C.C., Blackwood, D.J., Taylor, K.J. & Thomas, M.I. (1995): The anaerobic corrosion of stainless steels in simulated repository backfill environments. Report NSS-R-307. AEA Technology, Harwell, UK.

Naish, C.C., Blackwood, D.J., Thomas, M.I. & Rance, A.P. (2001): The anaerobic corrosion of carbon steel and stainless steel. Report AEAT/R/ENV/0224. AEA Technology, Harwell, UK.

Necib, N., Ambard, A., Bucur, C., Caes, S., Cochin, F., Fulger, M., Gras, J.-M., Herm, M., Kasprzak, L., Legand, S., Metz, V., Perrin, S., Sakuragi, T. & Suzuki-Muresan, T. (2018): Final report on C-14 behaviour in Zr fuel clad wastes under disposal conditions. CAST-2018-D3.20 Euratom 7th Framework Programme Project. European Comission, Brussels, Belgium.

Necib, S., Bumbieler, F., Duret-Thual, C., Bulidon, N., Crusset, D. & Combrade, P. (2017): Assessment of the resistance to environmentally assisted cracking (EAC) of C-steel casing and overpack in the COx claystone. Corrosion Engineering Science and Technology 52/sup1, 95-100. DOI: 10.1080/1478422X.2017.1336003.

Newman, R.C., Wang, S. & Senior, N. (2016): Understanding and Quantifying the Corrosion of Carbon Steel in Grouts Relevant to the Swiss L/ILW Repository. Nagra Work Report NAB 15-17 Rev.1.

Newmann, R.C. & Wang, S. (2013): Understanding and Quantifying the Corrosion of Carbon Steel in Grouts Relevant to the Swiss Nuclear Waste Repository - Status Reports 2011 and 2012. Nagra Work Technical NAB 13-08.

Newmann, R.C., Wang, S., Johnson, L. & Diomidis, N. (2013): Carbon steel corrosion and hydrogen generation in cementitious grouts. FORGE-2013-D0.09 Proceedings of the International Symposium and Workshop on Gas Generation and Migration (Luxembourg). Euratom 7th Framework Programme Project. European Comission, Brussels, Belgium.

Nishimura, T., Wada, R. & Fujiwara, K. (2003): Evaluation of Gas Generation Rates Caused by Metal Corrosion under the Geological Repository Conditions. R&D Kobe Steel Engineering Reports 53/3, 78-83.

Ogawa, Y., Suzuki, S., Taniguchi, N., Kawasaki, M., Suzuki, H. & Takahashi, R. (2020): Corrosion resistance of a cast steel overpack for high-level radioactive waste disposal in Japan. Materials and Corrosion 72/1-2, 52-66. DOI: 10.1002/maco.202011781.

Pourbaix, M. (1974): Atlas of electrochemical equilibria in aqueous solutions. National Association of Corrosion Engineers, Houston, Texas, USA.

Preece, C.M. (1982): Corrosion of steel in concrete. Report SKBF-TR-82-19. SKB, Stockholm, Sweden.

Preece, C.M., Arup, H. & Gronvold, F.O. (1981): The influence of hydrogen and carbon dioxide on the corrosion steel in anaerobic waste storage. Report SFR-81-09. SKB, Stockholm, Sweden.

Preece, C.M., Gronvold, F.O. & Frolund, T. (1983): The influence of cement type on the electrochemical behaviour of steel in concrete. In: Crane, A.P., ed., Corrosion of reinforcement in concret construction. Edited by Ellis Horwood Ltd, Chichester, West Essex, UK.

Rothman, A.J. (1984): Potential corrosion and degradation mechanisms of Zircaloy cladding on spent nuclear fuel in a tuff repository. Technical Report UCID 20172. LLNL, Livermore, CA, USA.

RWMC (1998): Verification test on advanced radioactive waste disposal systems. Report 1998 Volume 1 and 2. RWMC, Tokyo, Japan.

Sakuragi, T. (2017a): Final report on Zr alloys corrosion studies at RWMC. CAST-2017-D3.19 Euratom 7th Framework Programme Project. European Comission, Brussels, Belgium.

Sakuragi, T. (2017b): Report on corrosion behaviour of stainless steel. CAST-2017-D2.12 Euratom 7th Framework Programme Project. European Comission, Brussels, Belgium.

Sakuragi, T., Miyakawa, H., Nishimura, T. & Tateishi, T. (2012): Corrosion rates of Zircaloy-4 by hydrogen measurement under high pH, low oxygen and low temperature conditions. MRS Online Proceedings Library 1475, 311-316. DOI: 10.1557/opl.2012.592.

Sakuragi, T., Miyakawa, H., Nishimura, T. & Tateishi, T. (2013): Long-term corrosion of Zircaloy-4 and Zircaloy-2 by continuous hydrogen measurement under repository conditions. MRS Online Proceedings Library 1518, 173-178. DOI: 10.1557/opl.2013.66.

Sakuragi, T., Yoshida, S., Kato, O. & Tateishi, T. (2016a): Study of stainless steel corrosion by hydrogen measurement under deoxygenated, low-temperature and basic repository conditions. Progress in Nuclear Energy 87, 26-31. DOI: 10.1016/J.PNUCENE.2015.10.008.

Sakuragi, T., Yoshida, S., Kinugasa, J., Kato, O. & Tateishi, T. (2016b): Corrosion kinetics of stainless steel by hydrogen measurement under deep geological repository conditions - 16047. WM2016 Conference, Phoenix, Arizona, USA (2016).

Schenk, R. (1988): Untersuchungen über die Wasserstoffbildung durch Eisenkorrosion unter Endlagerbedingungen. Nagra Technischer Bericht NTB 86-24.

Schenk, R. & Noack, W. (1995): Wasserstoffbildung durch Eisenkorrosion unter den Bedingungen des planneden Endlagers KONRAD. Jahrestagung Kerntechnik, Nuremberg, Germany (1995).

Senior, N. & Martino, T. (2022): Nuclear Waste Consortium Research programme on corrosion and gas genereation: Phase 1 final report. Nagra Technical Report NTB 22-07.

Senior, N., Martino, T., Diomidis, N. & Gaggiano, R. (2023a): The anoxic corrosion of mild steel in a cementitious repository environment. Materials and Corrosion/in press. DOI: 10.1002/maco.202313765.

Senior, N., Martino, T., Diomidis, N. & Gaggiano, R. (2023b): The corrosion behaviour of non-ferrous metals in deep geological repository environments. Materials and Corrosion/in press. DOI: 10.1002/maco.202313772.

Senior, N., Martino, T., Gaggiano, R. & Diomidis, N. (2023c): Experimental factors and their impact on understanding corrosion in anoxic environments. Materials and Corrosion/in press. DOI: 10.1002/maco.202313771.

Senior, N.A., Martino, T., Diomidis, N., Gaggiano, R., Binns, J. & Keech, P. (2020): The measurement of ultra low uniform corrosion rates. Corrosion Science 176. DOI: 10.1016/j.corsci.2020.108913.

Shoesmith, D.W. & Zagidulin, D. (2011): The corrosion of zirconium under deep geological repository conditions. Journal of Nuclear Materials/418, 292-306. DOI: 10.1016/j.jnucmat.2011.07.028.

Simpson, J.P. & Schenk, R. (1989): Corrosion induced hydrogen evolution on high Level waste overpack materials in synthetic groundwaters and chloride solutions. MRS Online Proceedings Library 127, 389-396. DOI: 10.1557/PROC-127-389.

SKB (1999): Processes in the repository evolution. Technical Report TR-99-07. SKB, Stockholm, Sweden.

SKB (2006): Fuel and canister process report fro the safety assessment SR-Can. Technical Report TR-06-22. SKB, Stockholm, Sweden.

Smart, N.R. (2009): The corrosion behaviour of carbon steel radioactive waste packages: A summary review of Swedish and U.K: research. Corrosion 65/3, 195-212. DOI: 10.5006/1.3319128.

Smart, N.R. & Blackwood, D.J. (1998): An investigation of the effects of galvanic coupling on the corrosion of container and waste metals in cementitious environments. AEAT-0251, issue C. UK Nirex Ltd, Harwell, UK.

Smart, N.R., Blackwood, D.J., Marsh, G.P., Naish, C.C., O'Brien, T.M., Rance, A.P. & Thomas, M.I. (2004a): The anaerobic corrosion of carbon and stainless steels in simulated cementitious repository environments: A summary review of Nirex research. Report AEAT/ERRA-0313. AEA Technology, Harwell, UK.

Smart, N.R., Blackwood, D.J. & Werme, L. (2002a): Anaerobic corrosion of carbon steel and cast Iron in artificial groundwaters: Part 1 electrochemical aspects. Corrosion 58/7, 547-559. DOI: 10.5006/1.3277646.

Smart, N.R., Blackwood, D.J. & Werme, L. (2002b): Anaerobic corrosion of carbon steel and cast iron in artificial groundwaters: Part 2 gas generation. Corrosion 58/8, 627-637. DOI: 10.5006/1.3287691.

Smart, N.R., Blackwood, D.J. & Werme, L.O. (2001): The anaerobic corrosion of carbon steel and cast iron in artificial groundwaters. SKB Technical Report TR-01-22. SKB, Stockholm, Sweden.

Smart, N.R., Rance, A.P., Fennell, P.A.H., Gaggiano, R. & Padovani, C. (2021): Further studies on the anaerobic corrosion of carbon steel in alkaline media in support of the Belgian supercontainer concept. Materials and Corrosion/72, 75-93. DOI: 10.1002/maco.202011827.

Smart, N.R., Rance, A.P., Fennell, P.A.H. & Kursten, B. (2014): Effect of sulfur species on anaerobic corrosion of carbon steel in alkaline media. Corrosion Engineering, Science and Technology 49, 473-479. DOI: 10.1179/1743278214Y.0000000209.

Smart, N.R., Rance, A.P. & Werme, L.O. (2004b): Anaerobic corrosion of steel in bentonite. MRS Online Proceedings Library 807, 660-665. DOI: 10.1557/PROC-807-441.

Smart, N.R., Rance, A.P., Winsley, R.J., Fennell, P.A.H., Reddy, B., Dean, J. & Scott, D. (2010): Experimental studies of radiation-induced corrosion in support of the Belgium supercontainer concept: progress report. 10th JRT Meeting, Brussels, Belgium (2010).

Smart, N.R., Reddy, B., Rance, A.P., Nixon, D.J., Frutschi, M., Bernier-Latmani, R. & Diomidis, N. (2017): The anaerobic corrosion of carbon steel in compacted bentonite exposed to natural Opalinus Clay porewater containing native microbial populations. Corrosion Engineering, Science and Technology 52/sup1, 101-112. DOI: 10.1080/1478422X.2017.1315233.

Smith, V. & Jackson, C.P. (2013): Elicitation of the corrosion rate of lead in the LLWR. AMEC/200594/002 Issue 1. AMEC, London, UK.

Taniguchi, N., Kawakami, S., Kawasaki, M. & Kubota, M. (2004): Corrosion behaviour of carbon steel in contact with bentonite under anaerobic condition. EUROCORR, Nice, France (2004).

Taniguchi, N., Kawasaki, M. & Naito, M. (2010): Corrosion behavior of carbon steel in compacted bentonite saturated with simulated groundwater under anaerobic conditions. Zairyo To Kankyo 59/11, 418-429. DOI: 10.3323/jcorr.59.418.

Thomas, M.I. (1993): Corrosion of aluminium in cement grouts at elevated temperatures. AEA-D&R-0462. AEA Technology, Harwell, UK.

Thomas, M.I. & Naish, C.C. (1994): Corrosion of aluminium in replacement cement grouts at elevated temperatures: Further tests. APEC(94)P166. AEA Technology, Harwell, UK.

Wada, R., Nishimura, T., Fujiwara, K., Tanabe, M. & Mihara, M. (1999): Experimental study on hydrogen gas generation rate from corrosion of zircaloy and stainless steel under anaerobic alkaline condition. 7th International Conference Proceedings. Radioactive Waste Management and Environmental Remediation - ASME, Nagoya, Japan (1999).

White, J. (1987): Generic studies on the encapsulation of aluminium in cement. PETF(87)P61.

Wilding, C.R., Jones, D., Cole, G.B. & Evans, P. (1988): Phase 3: Generic modelling studies on aluminium. AERE R-13121, PETF(87)P104. AERE, Harwell, UK.

Wilding, C.R. & Naish, C.C. (1988): Phase 3: Generic modelling studies on aluminium. PETF(88)P70.

Xu, Q.F., Wang, W., Pang, X.L., Liu, Q.L. & Gao, K.W. (2014): Investigation of corrosion behaviours of high level waste container materials in simulated groundwater in China. Corrosion Engineering, Science and Technology 49/6, 480-484. DOI: 10.1179/1743278214Y.0000000191.

Yasuda, M., Fukumoto, F., Koizumi, H., Ogata, Y. & Hine, F. (1987): On the active dissolution of metals and alloys in hot concentrated caustic soda. Corrosion 43/8, 492-498. DOI: 10.5006/1.3583892.

Yoshida, S., Tanabe, H., Sakuragi, T., Nishimura, T., Kato, O. & Tateishi, T. (2013): Stainless steel corrosion rate under geological disposal conditions. Draft paper.

App. A Studies excluded from consideration

A.1 Iron and carbon steel

Tab. A-1: Excluded corrosion studies for iron and carbon steel in anoxic and highly alkaline environments

Reference	Reason(s) for exclusion
Heusler et al. (1958)	duration and measurement technique criteria
Kaesche (1965); Grubitsch et al. (1970); Grubitsch et al. (1979)	duration and measurement technique criteria
Preece et al. (1981); Preece et al. (1983)	duration and measurement technique criteria
Preece (1982)	duration and measurement technique criteria
Arup (1983)	duration and measurement technique criteria
Hansson (1985c)	duration and measurement technique criteria
Hansson (1985a)	duration and measurement technique criteria
Hansson (1985b); Hansson (1987)	duration and measurement technique criteria
Andrade & Page (1986)	duration and measurement technique criteria
Yasuda et al. (1987)	duration and measurement technique criteria
Grauer (1988)	measurement technique criterion
Naish et al. (1990); Naish et al. (1991)	duration and measurement technique criteria
Grauer et al. (1990)	duration criterion
Grauer et al. (1991)	duration criterion
Kreis (1991); Kreis & Simpson (1992)	duration criterion
Naish (1993)	duration, measurement technique and sensitivity criteria
Matsuda et al. (1994)	duration and measurement technique criteria
Schenk, Noack (1995)	duration criterion
Fujisawa et al. (1996)	duration criterion
RWMC (1998); Fujiwara et al. (2000)	duration and measurement technique criteria
RWMC (1998); Kaneko et al. (2004)	duration and measurement technique criteria
Fujisawa et al. (1999)	sensitivity criterion
Naish et al. (1995)	duration criterion
Naish et al. (2001)	duration, temperature and sensitivity criteria
Fujiwara (2002)	duration criterion
Fujiwara (2002); Kaneko et al. (2004)	duration and measurement technique criteria
Mihara et al. (2002)	duration and measurement technique criteria
Nishimura et al. (2003)	duration criterion
Kaneko et al. (2004)	duration and measurement technique criteria

Tab. A-1: Cont.

Reference	Reason(s) for exclusion
Smart et al. (2004a)	measurement technique and sensitivity criteria
Smart et al. (2004a); Smart (2009)	duration, measurement technique, temperature and sensitivity criteria
Honda et al. (2006)	duration criterion
Macdonald et al. (2007)	duration and measurement technique criteria
Azizi et al. (2008)	duration and measurement technique criteria
Azizi et al. (2008); Macdonald et al. (2009a)	duration and measurement technique criteria
Macdonald, Azizi (2008); Macdonald et al. (2009b)	duration and measurement technique criteria
Honda et al. (2009)	duration criterion
Macdonald et al. (2009a)	duration and measurement technique criteria
Macdonald et al. (2009b)	duration and measurement technique criteria
Macdonald et al. (2009b); Macdonald et al. (2010a)	duration and measurement technique criteria
Macdonald et al. (2010b)	duration and measurement technique criteria
Smart et al. (2010)	temperature, duration, measurement technique and sensitivity criteria
Jung et al. Aprill 10-14 (2011)	duration and measurement technique criteria
L'Hostis et al. (2011)	duration and measurement technique criteria
Duffó et al. (2013)	measurement technique criterion
Newmann et al. (2013)	duration criterion
Newmann & Wang (2013)	duration criterion
Smart et al. (2014)	temperature and duration criteria
He, Ahn (15.03.15); He et al. (2017)	duration and measurement technique criteria
Newman et al. (2016)	duration criterion
Chomat et al. (2014); Chomat et al. (2017)	measurement technique criterion
He et al. (2017)	temperature, duration and measurement technique criteria
Smart et al. (2017); Smart et al. (2021)	sensitivity criterion
Kursten et al. (2021); Kursten et al. (2017); Kursten et al. (2013); Kursten et al. (2011)	temperature, duration and sensitivity criteria
Smart et al. (2021)	temperature, duration, sensitivity and measurement technique criteria
Senior et al. (2023a)	temperature criterion
Senior et al. (2023c)	suspected experimental artefact due to lack of passivation

Tab. A-2: Excluded corrosion studies for iron and carbon steel in anoxic and near neutral environments

Reference	Reason(s) for exclusion
Heusler et al. (1958)	measurement technique criterion
González et al. (1980)	measurement technique criterion
Jelinek & Neufeld (1982)	duration criterion
Grauer (1988)	measurement technique criterion
Marsh & Taylor (1988)	temperature and duration criteria
Schenk (1988); Simpson & Schenk (1989)	duration and temperature criteria
Kreis (1991); Kreis & Simpson (1992)	duration criterion
Schenk, Noack (1995)	duration criterion
JNC (2000)	temperature and duration criteria
Smart et al. (2001)	temperature and duration criteria
Smart et al. (2001); Smart et al. (2002a); Smart et al. (2002b)	duration criterion
Mihara et al. (2002)	duration criterion
Taniguchi et al. (2004)	temperature and duration criteria
Honda et al. (2006)	pH criterion
Macdonald (2006); Macdonald et al. (2007)	measurement technique criterion
Taniguchi et al. (2010)	temperature and duration criteria
Jung et al. Aprill 10-14 (2011)	measurement technique and duration criteria
L'Hostis et al. (2011)	pH criterion
Dobrev et al. (2013)	temperature criterion
Duffó et al. (2013)	measurement technique criterion
Newmann et al. (2013)	duration criterion
Newmann & Wang (2013)	duration criterion
Newman et al. (2016)	duration criterion
Necib et al. (2017)	temperature criterion

Tab. A-3: Excluded corrosion studies for iron and carbon steel embedded in compacted bentonite

Reference	Reason(s) for exclusion
Smart et al. (2004b)	duration criterion
Dobrev et al. (2013)	duration criterion
Smart et al. (2017)	duration criterion
Ogawa et al. (2020)	duration criterion

A.2 Stainless steel and Ni alloys

Tab. A-4: Excluded corrosion studies for stainless steel and Ni alloys in anoxic and highly alkaline conditions

Reference	Reason(s) for exclusion
Yoshida et al. (2013)	no access to reference paper
Sakuragi et al. (2016a)	duration criterion
Sakuragi et al. (2016b)	duration and temperature criteria
Sakuragi (2017b)	measurement technique criterion

Tab. A-5: Excluded corrosion studies for stainless steel and Ni alloys under anoxic and near neutral environments

Reference	Reason(s) for exclusion
Federation of Electric Power Companies of Japan and Japan Atomic Energy Agency (2007)	no access to reference and lack of experimental details
Sakuragi (2017b)	temperature criterion
Xu et al. (2014)	measurement technique criterion

A.3 Aluminium

Tab. A-6: Excluded corrosion studies for aluminium in anoxic and highly alkaline environments

Reference	Reason(s) for exclusion
White (1987)	no access to the reference
Wilding et al. (1988); Wilding & Naish (1988)	no access to the reference
Lee & Wilding (1989)	no access to the reference
Thomas (1993); Thomas & Naish (1994)	no access to the reference and lack of experimental details
Thomas & Naish (1994)	measurement technique criterion
Smart & Blackwood (1998)	measurement technique criterion
Mendibide et al. (2021)	pH criterion
Caes et al. (2022)	measurement technique criterion

A.4 Lead

Tab. A-7: Excluded corrosion studies for lead in anoxic and highly alkaline environments

Reference	Reason(s) for exclusion
Goodwin & Guenther (1987)	duration and temperature criteria
Smith & Jackson (2013)	expert elicitation
Diomidis (2014)	expert elicitation

A.5 Zircaloy

Tab. A-8: Excluded corrosion studies for zirconium in anoxic and highly alkaline environments

Reference	Reason(s) for exclusion
Hillner (1977)	rates derived from fitted equation, with most of the original data at elevated temperatures
Hansson (1984); Hansson (1985b)	measurement technique criterion
Rothman (1984)	expert elicitation
Kurashige et al. (1999)	duration criterion
SKB (1999); SKB (2006)	expert elicitation
Wada et al. (1999)	duration criterion
Johnson & McGinnes (2002)	expert elicitation
Kogawa (2003)	measurement technique criterion
Nishimura et al. (2003)	duration criterion
Hélie (2004)	measurement technique criterion
Shoesmith & Zagidulin (2011)	expert elicitation
Sakuragi et al. (2012)	duration criterion
Andra (2013)	measurement technique criterion
Sakuragi et al. (2013)	duration criterion
Kato et al. (2014)	temperature and duration criteria
Bucur et al. (2017)	measurement technique criterion
Sakuragi (2017a)	duration and measurement technique criteria
Caes et al. (2018)	measurement technique criterion
Necib et al. (2018)	measurement technique criterion

Tab. A-9: Excluded corrosion studies for zirconium in anoxic and near neutral environments

Reference	Reason(s) for exclusion
Johnson (1977)	measurement technique criterion
Rothman (1984)	expert elicitation
Fraker & Harris (1990)	measurement technique criterion
IAEA (1998); IAEA (2006)	measurement technique criterion
SKB (1999); SKB (2006)	expert elicitation
Johnson & McGinnes (2002)	expert elicitation
Shoesmith & Zagidulin (2011)	expert elicitation
Andra (2013)	measurement technique criterion
Sakuragi (2017a)	temperature criterion

A.6 Magnesium

Tab. A-10: Excluded corrosion studies for magnesium in anoxic and highly alkaline environments

Reference	Reason(s) for exclusion
Cronin & Collier (2012)	temperature criterion