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Durability of Traditional and Innovative Disposal Container Materials and Coatings: State-of-the-Art and further Research within InCoManD

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Executive Summary

This document provides a consolidated state-of-the-art overview of current knowledge on containers designed to safely isolate heat-generating high-level radioactive waste in deep geological repositories (DGRs). These containers form a vital part of the multi-barrier safety system that ensures long-term protection of people and the environment. Their durability — especially their resistance to corrosion and mechanical stress — is essential, as they are expected to perform over time scales ranging from hundreds to hundreds of thousands of years.

The findings presented here are taken from recent research studies out of the EURAD programme and also from the EURAD-1 ConCorD project (Work Package 15, 2021–2024), which reviewed the performance of various container materials, including copper, carbon steel and silicon carbide. The report covers experimental results under relevant disposal conditions, the impact of manufacturing and sealing processes, and the current capabilities of modelling tools to simulate the complex underground environment in which these containers will operate.

In addition to summarising knowledge on traditional materials, the document highlights recent progress and remaining challenges related to innovative ceramic-based containers. Key issues include ensuring effective sealing and mechanical integrity, particularly under harsh and evolving conditions over long periods.

The report also emphasizes the importance of understanding how different environmental and mechanical factors interact to influence container degradation. Neither corrosion nor stress alone can fully explain long-term behaviour, and both must be studied together.

Finally, this state-of-the-art sets the stage for future work, especially the EURAD-2 InCoManD project (Work Package 9), which will build on these findings to improve testing methods, refine models, and explore promising new materials and design solutions for safer and more reliable waste containment. Research activities within InCoManD are hence briefly described throughout this document.

Keywords

Ceramics

Coatings

Corrosion Resistance

Deep Geological Repository

Disposal Container Materials

Durability

Engineered Barriers

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High-Level Radioactive Waste

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Transport Modelling

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Glossary

AFM	Atomic Force Microscopy
ATZ	Alumina Toughened Zirconia
BCV	Bentonite Cerny Vrch
CBG	Cement-bentonite grout
CMEA	Coupled Multiectrode Array
CVD	Chemical Vapor Disposition
CSC	Cold Spray Coating
CT	Computer Tomography
Cu-OFE+P	Oxygen-free Phosphorus-containing Copper
Cu-OFHC	Oxygen-free high conductivity Copper
DGR	Deep Geological Repository
eAFM	Electrochemical Atomic Force Microscopy
EB	Electron Beam
EBS	Engineered Barrier System
EDS	Energy-Dispersive X-ray Spectroscopy
EIS	Electrochemical Impedance Spectroscopy
ER	Electrical Resistance
FEBEX	Bentonite extracted Cortijo de Archidona deposit (Almería, Spain)
FZ	Fusion Zone
GDF	Geological Disposal Facility
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
HAZ	Heat-Affected Zone
HLW	High-Level radioactive Waste
IC-A	In situ corrosion experiment (Mont Terri)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MaCoTe	Materials Corrosion Test (Grimsel)
MAG	Metal Active Gas
MIC	Microbiological Influenced Corrosion
ML	Machine Learning
MW	Microwaves
MX-80	Wyoming Bentonite
OCP	Open Circuit Potential
PAW	Plasma Arc Welding

PVD	Physical Vapor Disposition
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscope
SNF	Spent Nuclear Fuel
SRB	Sulphate-Reducing Bacteria
SSRT	Slow Strain Rate Tests
TIG	Tungsten Inert Gas
TSC	Thermal Spray Coatings
XPS	X-ray Photoelectron Spectroscopy
XRD	X-ray Diffraction
YCW	Young Cement Water
ZTA	Zirconia Toughened Alumina

1. Introduction

Deep Geological Repository (DGR) has become the most favourable and internationally agreed option to safely dispose heat generating waste that includes (vitrified) high-level radioactive waste (HLW) and spent nuclear fuel (SNF). Such a disposal requires a sustainable multi-barrier concept to ensure safe containment of the radioactive waste and to limit potential radionuclide migration to negligible levels in the long-term, i.e., for time periods of up to one million years. Such multi-barrier concepts are based on a stable host rock formation like, e.g., claystone, crystalline rock, or rock salt formations in combination with additional geo-technical and technical barriers referred to as engineered barrier systems (EBS) (IAEA, 2020; Lommerzheim *et al.*, 2023). Disposal containers are essential technical barriers of any repository concept as they are needed for waste-form packaging, handling, emplacement, and possibly retrieval or recovery. Their safety functions are focussed on confinement, sub-criticality, shielding, decay-heat transfer under operational and transient disposal conditions for a certain period depending on the overall repository safety concept.

Depending on the different host rock types, specific containers are under consideration in several countries (Bollingerfehr, 2023), with steels and copper being the most often considered container materials. However, many other materials are currently under consideration to develop innovative containers. Two main options are in fact being studied: traditional materials improved by a dedicated coating, e.g., titania (TiO_2), chromium nitride (CrN), or copper, and novel materials such as monolithic (oxide or carbide) ceramics (Gaggiano & Diomidis, 2023). The coating could be used to suppress corrosion of the metallic container oror minimise it, thereby providing more flexibility, notably with respect to gas management in the geological disposal facility (GDF). Ceramics, that do not produce gaseous hydrogen H_2(g) when they are altered, or highly corrosion resistant metals that produce insignificant amounts of H_2(g) (contrary to steels), could allow for a less complex waste management process and also, provide a more robust safety case. Both routes require selection of appropriate materials and of their applicable fabrication and deposition methods, and validation of the materials durability under realistic field conditions among which transient ones are crucial to consider (see chapter 2). However, to control the disposal containers lifetime, stable near-field geo-chemical conditions are favoured, which is why these containers are often combined with a geo-technical barrier such as, e.g., cement-based or bentonite buffers, especially in crystalline and claystone formations. Such buffers stabilise conditions in the container near-field and thus protect them from mechanical damage and corrosion (Lommerzheim *et al.*, 2023).

The geological disposal conditions subject the container to various challenges, corrosion resistance being one of the most critical. Container lifetimes are typically calculated based on the time-dependent corrosion behaviour alone, with the implicit assumption that the container has been designed to remain structurally stable for its required lifetime of usually several hundreds to hundred thousand years. However, for some component materials and designs, there can be significant interactions between mechanical and corrosion degradation modes that could affect the ultimate failure time. Even though the durability of several component materials subjected to corrosion processes under selected environmental conditions have been previously studied in detail, the coupling between mechanical processes and corrosion phenomena calls for further study, and assessment of the impact of joint degradation modes on component lifetimes will result in a more robust and defensible safety case. Besides, as corrosion occurs in a thin interfacial surface layer between the component outermost surface and the environment, specific R&D work is required to understand the long-term performance controlled by the entire EBS. Indeed, this latter is complex, made of different materials (excluding here the containers), for instance the host rock and cement-based materials or bentonite (backfills, buffers), and characterised by various, impactful conditions such as the water chemistry, the microbial activity, the stress load, the temperature, the radiation source, etc. (see chapter 3).

To extrapolate experimental findings gained from short-term (weeks to years) laboratory or field testing to the extreme long-term of several thousand or even 100,000 years, validated analytical and numerical simulation tools become an essential part of any safety case. Thus, numerical modelling is vital, but it needs to be strongly connected to experimental studies. In fact, experiments should gain from modelling and vice versa: modelling must be validated by experimental data and simulation tools can be fed by experimental data, while modelling outcomes can help understanding experimental results (chapter 4).

Within EURAD-1 Work Package 15 ConCorD (Container Corrosion under Disposal conditions), based on a comprehensive review of the existing knowledge, several aspects of container degradation mechanisms have been recently updated (Abdelouas *et al.*, 2024; Smart *et al.*, 2024). Studies within ConCorD included traditional materials like copper and carbon steel in clay-based environments with special focus on transient disposal conditions, as well as novel materials typically exhibiting very low corrosion rates (e.g., stainless steel, nickel- and titanium-based alloys). Novel materials also included ceramic materials, although these latter were principally studied in the perspective of their sealing. Other tasks were addressing radiation effects on corrosion processes and container lifetime, the microbial activity in highly compacted bentonite to assess the potential for microbially influenced corrosion (MIC) on container materials, corrosion during transients considering the evolution of the repository environment in comparison to assumed steady conditions, and finally predictive modelling. In summary, many valuable outcomes from ConCorD significantly increased the level of knowledge about long-term container degradation mechanisms, but many aspects still need further studies to enhance disposal container material and design options, and both safety assessment and robustness.

Within EURAD-2 Work Package 9 InCoManD, three scientific tasks (see chapters 2 to 4) have been defined for further research to **gain additional knowledge** needed **to enhance the reliability of disposal container solutions**; importantly, the **research effort will be specifically implementation-oriented**, *i.e.*, related to one or several disposal concepts currently studied by the organisations in charge of these projects. **The current document therefore constitutes a hybrid document between a state-of-knowledge (SoK) report and a White Paper.** Thus, **it summarises and evaluates the latest results about container materials durability under disposal field conditions** principally, but not only, in the light of the most relevant outcomes from EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024), **and** it briefly **describes the forthcoming studies defined to go beyond this SoK within** the EURAD-2 Work Package 9 **InCoManD**.

In chapter 2, novel materials and innovative solutions are addressed. The former include bulk, monolithic ceramics like alumina (Al_2O_3) and silicon carbide (SiC) and their potential large-scale application for manufacturing disposal containers, including sealing/welding processes. The latter deals with coatings deposited by different techniques and of different nature, *i.e.*, metallic (e.g., Cu), ceramic (e.g., CrN) or composites of those (e.g., Cu/Al_2O_3). For both cases, issues like mechanical stability, corrosion, and chemical resistance are thoroughly tackled. Finally, a very first look at life cycle assessment (LCA) and life cycle costing (LCC) is given to define how to evaluate the technological and economic feasibility of the different selected integrated processes (raw materials and manufacturing).

In chapter 3, the evaluation of materials corrosion resistance to provide insights on containers durability is addressed. Well-established materials are principally considered, but novel materials are also discussed to some extent. Results of laboratory and field tests of chemical attacks are presented; the effect of individual and coupled important parameters such as temperature, redox conditions, irradiation, and microbial activity are put forward; benchmarking of different set-ups is also provided.

In chapter 4, the emphasis is on the experimental and modelling evaluation of degradation mechanisms, with a focus on threshold mechanical loads and stress levels relative to the material's microstructure. The discussion explores the combined effects of mechanical and corrosion processes to better understand stress corrosion cracking (SCC) in key materials such as copper and steel, commonly used in nuclear waste containers. Additionally, the chapter highlights recent progress in geochemical modelling, addressing transient conditions, reactive transport, and the relationships between container strength, corrosion behaviour, and pressure variations.

2. Innovative HLW and SNF container materials

In any geological disposal facility (GDF), containers for spent nuclear fuel (SNF) and high-level radioactive waste (HLW) must provide long-term integrity and isolation to keep the radioactive waste away from groundwater, and to prevent potential early release of radionuclides to the environment underground. To fulfil the requirements linked to these functions, containers must exhibit both mechanical and chemical durability, given that the containers will be subjected to harsh conditions, including mechanical stresses of several MPa and corrosive groundwater. Most common materials studied and developed so far to manufacture a sustainable container are metals. But ceramics have also been of interest because, despite some weaknesses addressed hereafter, they have the advantage of not producing gaseous hydrogen $H_{2(g)}$ when they experience corrosion.

This ceramic option has been considered since the 1980s (Mattsson, 1980; Bienek *et al.*, 1984; Adams *et al.*, 2000; Wötting & Martin, 2007; Kerber & Knorr, 2013; Holdsworth, 2013; Baroux & Martin, 2016). However, ceramics, at least in their monolithic form, usually exhibit inferior mechanical properties than metals, such as strength and toughness (especially low fracture toughness), which poses a huge challenge when considering these materials to manufacture disposal containers. For this reason, the wall thickness of a ceramic container must be in the range of some centimetres, which is particularly difficult due to the complexity of the very process of ceramic manufacturing, notably the drying and the sintering parts (Debelle *et al.*, 2024; Abdelouas *et al.*, 2024). Another major issue concerns the container sealing itself (*i.e.*, the tight joining of the body and the lid of the container), as the conventional methods used for metal containers are unsuitable for ceramics due to their high melting points. This requires the development of a sealing approach (sealing materials associated to specific heating methods) adapted to ceramics. To finish, current global manufacturing capabilities are limited when considering the size of the pieces required for the disposal of HLW, and even more for SNF. Despite these drawbacks, which could be addressed with sufficient time and money investment, ceramics possess significant key strengths, the major one being the fact that they do not lead to gas production when they experience corrosion. Given that no other industries require large ceramic (pressure) vessels, funding for research and development of a ceramic waste container must come from the nuclear industry.

Effort to investigate this route is regularly renewed, which led to a better analysis of potential ceramic materials for nuclear waste containment. Within the framework of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024), two promising approaches have emerged for enhancing the integrity and durability of containers based on advanced materials able to withstand the harsh conditions associated with a DGR concept. The first approach consists in using bulk ceramics, such as alumina (Al_2O_3) (Debelle *et al.*, 2024) and silicon carbide (SiC), as materials for the container. These ceramics exhibit good chemical stability and high mechanical strength. However, their robustness in the long term and operational conditions yet remain to be validated. As abovementioned, one of the key challenges is the sealing of a ceramic container. Sealing assisted by microwaves is a technological solution of interest since it allows a rapid and localised temperature increase without affecting the integrity of the bulk ceramic container itself and of the inner nuclear waste form. The second approach is based on ceramic coatings on metallic containers to provide flexibility during the operating phase by delaying the metal corrosion using a coating that will eventually be degraded but only after a given period, or by mitigating the metal corrosion using sacrificial coatings (Holdsworth *et al*., 2018). Coatings require processing temperatures in general lower than for their bulk counterparts and are more cost-effective; several materials could also be used at the same time in the form of tailored multilayer structures to combine these compounds properties. However, there are still challenges to be tackled, like ensuring the uniform adhesion of the coatings, mitigating their long-term degradation, and maintaining their structural integrity over time. Note that in addition to ceramic coatings, advanced metallic coatings are also of interest for this application (see section 2.2).

Both innovative approaches are promising for radioactive waste disposal. They rely not only on the choice of materials but also on the associated fabrication techniques as demonstrated in the following sections reviewing the state of the art in the field, including results obtained, unless otherwise stated, in EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) and prospects included in the work plan of EURAD-2 Work Package 9 InCoManD.

2.1 Large scale ceramics and sealing processes

2.1.1 General overview

Ceramics are inorganic (non-metallic) materials. They are differentiated into two families: traditional (such as bricks and tiles) and advanced ceramics (used in automotive industry, microelectronics, aeronautics, energy, etc.). Ceramics generally share common characteristics like brittleness, refractoriness, chemical stability, oxidation resistance and hardness due to the mixed ionic-covalent nature of their bonding. In general, oxide ceramics (e.g., Al_2O_3) rely on an ionic bonding at the atomic level, whereas non-oxides (e.g. SiC) are covalent.

Their fabrication processes involve several key steps. In general, fine synthetic powders are used as raw materials for advanced ceramics. Colloidal suspensions or stiff pastes are then formulated from these powders using (organic) additives. There are a large variety of shaping processes used. The most common ones are slipcasting, tape casting, gel casting, granulation and pressing and extrusion (with feedstocks being pastes in these latter cases). There is also a growing interest in 3D-printing today. The as-obtained shaped products called “green bodies” then undergo drying and debinding (release of the organic additives) before being sintered at high temperature (typically from 1300 °C to 1800 °C) to close the porosity and reach the maximum density (note that it is almost impossible to totally eliminate porosity, but this latter can be closed, meaning that it does not allow the water to migrate as when it is open). Controlling all these interdependent processing steps is particularly difficult for large and thick parts such as those targeted to be used as large-scale ceramic containers.

Several ceramic materials (see Table 1) have been (conceptually) considered as viable options, including alumina (Al_2O_3), silicon oxide (SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), partially stabilized zirconia (PSZ), and titania (TiO_2). These materials were chosen due to their chemical stability, mechanical properties, and commercial availability. However, recent attention has primarily focused on alumina-based compounds and SiC as the most promising candidates. The current SotA document is centred on these two materials; further studies needed to address manufacturing challenges and to ensure their feasibility for long-term nuclear waste containment are also briefly proposed.

It has to be noted that there are other promising candidates/approaches, likely less described in the literature, but that may have an interest for nuclear waste disposal due to their excellent radiation resistance, thermal stability and chemical durability. Even if, at present, these materials are mostly envisaged as waste forms, i.e. confinement matrices and not container materials, they are briefly listed below, emphasising their properties of interest for waste disposal.

- Synroc (Synthetic Rock): A titanate-based ceramic developed in Australia, designed to immobilize high-level radioactive waste which is made of minerals like hollandite, perovskite, zirconolite, and rutile and which is highly resistant to leaching and thermal stress (Carter *et al.*, 2009).
- Glass-Ceramic Containers: A hybrid approach combining vitrification (glass) and ceramic crystallization, which offers improved mechanical strength and lower leaching rates compared to pure glass waste forms. Examples are iron phosphate glass-ceramics and zirconium-based glass-ceramics (Bernardo & Maschio, 2011).
- High-Entropy Ceramics: A new class of materials with multiple cations (at least 5), enhancing radiation tolerance which is suitable for immobilizing actinides and fission products (Tunes *et al.*, 2023).
- Zirconium-Based Ceramics (Zirconolite): Zirconolite ($CaZrTi_2O_7$) is highly durable and resistant to radiation damage (Foxhall *et al.*, 2013).

- Perovskite-Structured Ceramics: Materials that can host a variety of radioactive elements, particularly strontium and caesium, materials resistant to radiation-induced amorphization (Li *et al.*, 2025).
- MAX Phases (Mn+1AXn): A class of ceramics with both metallic and ceramic properties, which have excellent mechanical strength and high tolerance to radiation damage (Whittle *et al.*, 2010).

	SiO_2-MgO	Al_2O_3 (96-99.1%)	Al_2O_3 (99.8%)	ZrO_2-MgO	ZrO_2-Y_2O_3	TiO_2	SiC	Si_3N_4-Y_2O_3
Gross density (g/cm^3)	2.2-2.8	3.80-3.82	3.96	5.74	6.08	4.26	3.10	3.21
Flexural strength (MPa)	110-180	280-350	500	500	1000	69-103	350	750
Compressive strength (MPa)		2000	4000	1600	2200		2000	3000
Fracture toughness (MPa√m)		4.0	4.3	8.1	10.0	2.5	3.8	7.0
Elastic modulus, dynamic (GPa)	70-120	270-340	380	210	210	283	350	305
Vickers hardness (GPa)		14-17	18	13	13		25	16
Thermal conductivity (W/mK)	2-5	24-28	30	3	2.5	8.8	100	21
Thermal expansion, CTE (10^{-6}/ºC)	4-7	7.1-7.3	7.5	10.2	10.4	9.4	3.5	3.2
Maximum operating temperature (ºC)	1000	1400	1500	850	1000		1800	1600
Melting point (ºC)		2015		2700		1840	2700	2700

Table 1: Typical properties of ceramics for disposal containers (Holdsworth, 2015). Main properties of interest are highlighted in red (flexural strength, fracture toughness, thermal expansion, melting point).

2.1.2 Alumina-based ceramic containers

The study of alumina-based large ceramic containers has been carried out essentially for nuclear waste disposal applications, and mostly conceptually. The concepts developed by several organisations are described in detail in the EURAD-1 Work Package 15 ConCorD reports (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) and are thus not reported here. In contrast, a summary of major achievements from EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) in the field of alumina-based HLW disposal containers is presented hereafter.

IRCER-EMSE worked together on the development of new sealing formulations for alumina-based (e.g., silico-aluminate materials with a high content of alumina) ceramic containers and the test of their performance when sealing was performed using microwaves (MW). The major achievement was the unprecedented improvement of the microwave coupling allowing for a fast sintering which, as a result, should allow in real conditions to limit the increase of the temperature during the sealing process in the core of the container containing the nuclear waste form. The new sealing formulations had also to satisfy the mechanical and leaching resistance specifications, which are the same as those defined for the material of the container itself, and that depend on the DGR concept.

More specifically, in a first approach, the research was focused on the exploitation of the hetero-aggregation phenomenon in water-based suspensions between an alumina micro-powder and a silica nano-powder carrying opposite surface charges. The generation of surface charges was linked to the zeta potential resulting from the acid-base equilibria arising in water. Following this processing route made possible to prepare very homogeneous and intimate blends of the two materials at the nanoscale. Knowing that blends were composed of two materials exhibiting different MW coupling efficiencies, the idea was actually to derive benefit locally (e.g. at the powder grain level) of the best-coupling material to get a localized, efficient, homogeneous and fast heating process which is key for the application.

The first MW sealing tests of these hetero-aggregated alumina-silica blends showed an increased MW coupling validating the overall strategy followed. In order to go a step further, silicon carbide was added to the alumina-silica formulations in low quantities (maximum of 2 vol.%). SiC is well-known as one of the best ceramics in terms of MW coupling. Contrary to previous studies performed with the addition of SiC micron-size powders which showed no improvement, here a nano-SiC (typical size of 20 nm) was added. This SiC was covered with a native silica layer allowing to implement hetero-aggregation the same way as with nano-silica. Consequently, a strong boost of the MW coupling was observed as illustrated in Figure 1. This can be considered as a breakthrough in the field.

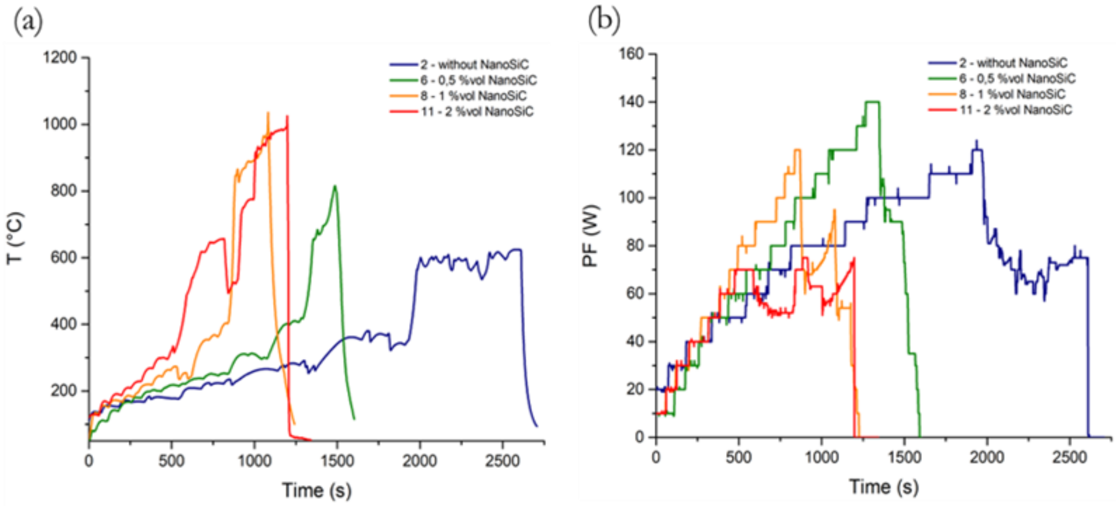

Figure 1: Comparison of microwave coupling for samples containing different amounts of nano-SiC (a), Corresponding forward power input during the microwave tests necessary to reach 400 °C (b).

Concerning the very positive effect of nano-SiC on MW coupling, it is assumed that this is not only due to the material itself and to its very homogeneous distribution throughout the volume thanks to the hetero-aggregation, but there might also be a "pinning" of the electromagnetic field on the nano-SiC. However, at this stage, it remains an assumption that has still to be confirmed. Another issue that has to be studied is the fact that the oxidation of SiC above 800 °C during the sealing can produce bubbles that may degrade the mechanical properties and the leaching resistance if bubbles percolate.

Research on the very topic of alumina-based bulk ceramic materials for a disposal waste container is currently only tackled by Andra (Debelle *et al.*, 2024). Related R&D activities aim to investigate, in parallel to more traditional options (such as slip casting of an aluminosilicate), new processes for the shaping of large alumina parts. The gel-casting method, adapted for the container application, and using pure alumina, is thus a solution of particular interest. This work is done in collaboration with Galtenco Solutions, and in 2022, a small-scale pseudo-container was produced, with a wall thickness of 2 cm, which is not sufficient for the requirements inside Cigéo, but an encouraging result (Figure 2). It is important to mention that the gel-casting method has not spread over industry because of the need to use toxic organic compounds; to circumvent this issue, researchers are studying natural protein-based gelformers (Babashov & Varrik, 2023). Other issues being addressed are optimisation of sealing processes (including sealing material compositions and heating methods) and sealing geometries. For instance, an easy to implement (even in a radioactive environment) solution has recently been tested, consisting of depositing a commercial enamel on the lips to be sealed using an air-pressured gun, and melting this enamel with an indirect resistance furnace (Figure 2). Both parts were sealed, but effectiveness of this joining technique must be evaluated.

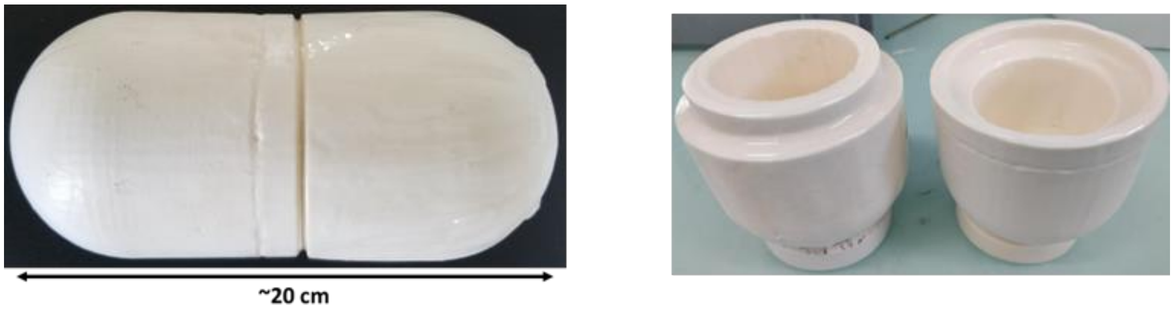

Figure 2: Picture of a 1:8 scale alumina HLW container as designed and constructed by Galtenco Solutions and Andra (left). The wall is 2 cm thick. Both parts were sealed using a procedure described in (Debelle et al., 2024). The lid and body lips are designed to optimize sealing; the shiny parts on the lips indicate the presence of an enamel deposit used for subsequent sealing (right).

The flexural strength of this alumina elaborated by gel-casting has been evaluated using 3-point bending tests, and the measured stress reaches more than 400 MPa (but the Weibull modulus must me improved); this value allows, in combination with a large thickness (in the order of 3-4 cm), a container to withstand unprecedented mechanical loads for this type of ceramic pieces. The resistance to leaching solutions of alumina-based materials is reported in chapter 3.

2.1.3 SiC-based ceramic containers

Silicon carbide (SiC) has been identified (Knorr *et al.*, 2008) as a viable material for HLW and SNF container fabrication. While previously only silicon-impregnated (SiSiC) and recrystallized SiC (RSiC) were used for large components, advancements now allow the use of sintered SiC (SSiC), including high-strength grades. Recent research focuses on SiC's corrosion resistance, crucial for its application in HLW disposal. Corrosion tests by General Atomics and Westinghouse Electric (Deck *et al.*, 2018) showed SiC's high resistance, with a dissolution rate of just 1 µm/yr under reactor conditions. Studies also demonstrated that doping SiC with chromium (Cr) enhances both corrosion resistance and mechanical properties (e.g. fracture toughness by 25-50%) (Lobach *et al.*, 2018 and 2020). For geological disposal, further research is needed to understand SiC corrosion mechanisms at lower temperatures (< 90 °C) and site-specific environmental conditions. Two primary methods for joining SiC segments have been explored:

<u>Laser Joining:</u> Uses a pure oxidic braze filler (CERALINK®) melted by a laser beam, producing gas-tight, strong, and crack-free joints without pre-treatment (Knorr *et al.*, 2008).

<u>Glass-Ceramic Soldering:</u> Uses Y_2O_3-Al_2O_3-SiO_2 (YAS) material, with shear strength improving as soldering temperature increases, reaching 51.7 MPa at 1400°C (Wang *et al.*, 2020).

These findings highlight SiC strong potential for nuclear waste containment due to its durability, corrosion resistance, and advanced joining techniques.

In the following paragraphs, major achievements from EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) in the field of SiC-based HLW disposal containers are summarized.

KIPT carried out the optimization of technological parameters related to SiC sintering (Lobach *et al.*, 2024). The optimum parameters of the sintering process for obtaining high-density SiC samples were established (T = 2050 °C; t = 30 min; P = 40 MPa; heating rate of 200 °C/min). Then SiC mixtures with Cr additives (from 0.3 to 0.9 wt.%t) were prepared. Visual inspection showed that black dots appear in the silicon carbide structure with increasing chromium concentration, which are possibly, carbon, silicides or chromium carbides. According to Raman spectroscopy, the obtained SiC (Cr) samples belong to the polytype 6H-SiC.

Silicon carbide samples with chromium concentration from 0.3 to 0.5 wt.% have the highest microhardness (25 GPa) and nanohardness (37.8 GPa), see Figure 3 (left). Samples of pure SiC and Cr-doped SiC (0.3 wt.% and 0.5 wt.% Cr) were tested for long-term corrosion resistance in distilled water at 90 °C, see Figure 3 (right). The corrosion test results have shown that pure SiC samples are soluble in water. Chromium-alloyed samples dissolve at the early stage of the test, increase in weight at the intermediate stage, which may be due to the formation of protective films, and begin to dissolve again after 3500 hours of testing. The average dissolution rate of these materials is in the range of 0.095 to 0.16 µm per year. Yet, dissolution rates under representative disposal field conditions must still be determined.

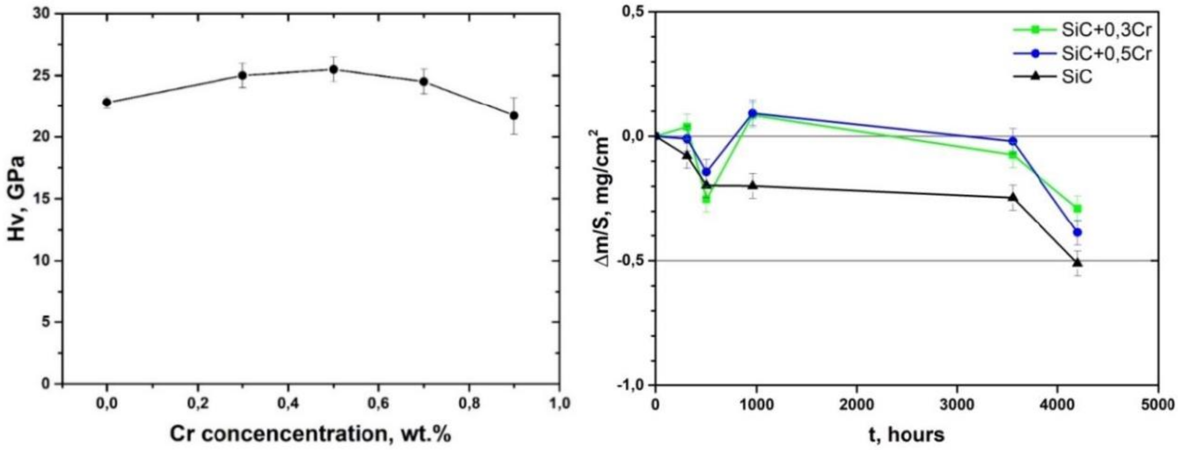

Figure 3: Hardness of Cr-doped SiC samples as a function of the Cr concentration (left), weight change of similar samples as those studied for the hardness estimate (right) (Lobach et al., 2024)

In short, Cr-doped SiC has real advantages over pure SiC, with higher corrosion resistance (at least in pure water), and higher hardness. However, SiC is obviously more expensive to produce and machine than conventional materials, which is an issue. KIPT pointed out that further research and development is needed to optimise the alloying and sealing methods of SiC for container applications and to fully evaluate its feasibility compared to traditional materials. The mastering of sealing, which has not really been studied in detail yet, is more specifically an issue in order to be able to assemble various segments of SiC to build up the overall SiC container. Indeed, fabricating a large SiC container as a single block seems hardly feasible in the present state of the art.

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

New materials and processing methods, as well as new sealing techniques are studied within InCoManD task 3 of EURAD-2 Work Package 9 InCoManD. This task is not just a continuation of what was done in task 2 of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) with some refinements; it aims to go beyond the current state of knowledge with the study and improvement of new bulk ceramic materials and manufacturing routes for the container.

<u>Alumina-based ceramic containers:</u>

Andra, in collaboration with Galtenco Solutions, focuses on identifying a suitable alumina-based ceramic material and optimising its manufacturing process using the gel-casting method. The primary goal is to develop a material with a high mechanical strength, verified through, e.g., bending tests. Given the challenges in achieving a sufficiently large thickness, optimising all steps of the gel casting process is crucial. Additionally, a composite material combining alumina with zirconia (5–20% in weight) is explored to enhance mechanical strength, rupture toughness and durability. Another issue addressed is the sealing of the alumina-based containers. Andra is collaborating with IRCER and EMSE to develop an innovative microwave technique allowing a localised, fast and high temperature heating of the sealing material. For this purpose, EMSE will evaluate the thermal and dielectric properties of the materials and is also in charge of developing the dedicated heating system. In parallel, IRCER is developing specific formulations based on intimate blends of ceramic powders relying on a hetero-aggregation process. The formulations are mostly based on silico-aluminates, with the addition in quite small quantities of materials allowing a strong coupling of microwaves such as nano-SiC and/or glass. During InCoManD, SiC fibres will also be tested as a microwave susceptor. An original testing method using centrifugal force will be implemented to provide a first evaluation of the mechanical resistance of sealed coupons; this method, although not fully quantitative, offers the advantage of measuring several samples at the same time, which allows reducing the experiment time and testing more rapidly a larger number of parameters like sealing material, interface design, and heating method.

<u>SiC-based ceramic containers:</u>

In collaboration with VTT, EMSE and GRS, KIPT focuses on silicon carbide doped with chromium (SiC/Cr). The objectives are to improve and qualify the innovative materials previously identified in EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024), develop manufacturing methods to enhance corrosion resistance, investigate SiC/Cr ceramics for container sealing and bonding. Various experiments and analyses are conducted, such as high-speed sintering of SiC/Cr ceramics under pressure, corrosion resistance measurement, mechanical testing and advanced microscopy. The development and testing of SiC/Cr ceramic joints (for instance with metallic fillers), while analysing their corrosion resistance (in conditions applying to one or several DGR concepts) and mechanical strength is also a major issue, alike the case of alumina-based containers.

<u>Nota Bene:</u> Developing ceramic-based HLW disposal containers is challenging, whatever the ceramics under concern, particularly in producing large and thick parts with sufficient mechanical resistance and ensuring a reliable sealing. However, through a combination of advanced manufacturing techniques (gel casting, high-speed sintering), innovative sealing methods (microwave-assisted), rigorous durability testing and modelling (tasks 4 and 5 of EURAD-2 Work Package 9 InCoManD), the feasibility study is realistic. Note the key role played by sealing. Indeed, in case the production of very large ceramic containers would face issues, a fabrication exploiting the assembly of smaller "segments" could be a fall-back option, but it will require a bonding/sealing strategy anyway, hence the key role of this process.

2.2 Coatings

This SotA proposes to briefly review the coating deposition methods that have been implemented in EURAD-1 Work Package 15 ConCorD (Munoz *et al.*, 2024). It includes cold spray, electrodeposition, physical vapor deposition and arc welding to hermetically seal the container. A few additional studies, outside the EURAD community (more precisely, in the petroleum industry), are also provided to show the range of possibilities in the field of corrosion protective coatings.

2.2.1 Key challenges for effective protective coatings

To obtain a coating that does protect the container, several key issues must be addressed. First, an ultra-low porosity must be achieved to ensure that water does not reach the metallic container too quickly and/or locally, because both cases would completely suppress the advantage of using a coating. Typically, a porosity level lower than 2% (and perhaps even less) should be the target. Second, an excellent adhesion of the coating on its substrate is required, for the same reasons as above-mentioned. It is worth mentioning that several methods exist to test adhesion, like micro-indentation, scratch testing and cyclic impact testing, 4-point bending tests (Khlifi *et al.*, 2013; Kumar *et al.*, 2025). Wear resistance is also an important feature to consider. Third, as for any other material form and nature, coatings must exhibit a sufficient resistance to (or durability under) disposal field conditions, principally regarding interaction with groundwater.

2.2.2 Chemical and Physical Vapor Deposition (CVD, PVD)

Chemical Vapor Deposition methods (CVD) involve the chemical reaction of gaseous precursors in a chamber, where the desired coating material forms on the substrate surface. However, this method requires high temperatures to be implemented, which might be an issue with respect to the waste form. Diamond-Like Carbon (DLC) films, exhibiting a high chemical inertness, could yet be an interesting protection to explore (Darmawan *et al.*, 2024) for this application, as the temperature required for their deposition is lower (less than 300 °C).

Physical Vapor Deposition (PVD) is a vacuum-based deposition process where the coating material is vaporised from a solid source and then condensed onto the surface of the substrate (container) (Baptista *et al.*, 2018). PVD coatings have good corrosion protection compared to coatings that are deposited by traditional spraying. Despite the small thickness of the PVD coating layers (in the order of 5-10 µm), they have much lower porosity than the coatings deposited by spraying.

On a large panel of composition (TiN, ZrO_2, TiO_2, Al_2O_3, and MoS_2), the study of Fusco *et al.* is the only one which presents corrosion tests of PVD films in aerated 1 M NaCl solution over a period of 5 months. Results do not show any weight change of the coated samples. However, penetration rate was not evaluated, and it must be noted that the protective effect of the films was not demonstrated either because of too thin coatings (hundred nanometres) (Fusco *et al.*, 2016).

Advantage of the PVD methods is the environmental friendliness of the process (Muñoz *et al.*, 2024, Belous *et al.*, 2018). PVD also allows to deposit a large panel of compositions. Of particular interest was titanium oxide (TiO_2) and chromium-nitride (CrN). CrN seems to be the most promising coating material in terms of corrosion resistance (Muñoz *et al.*, 2024, Abdelouas *et al.*, 2024), as when deposited under proper conditions, no traces of corrosion were found after 296 hours of testing at 20 °C in 3% NaCl solution or after 4,000 hours in distilled water at 90 °C (Figure 4); of course, corrosion resistance must be now evaluated for more representative disposal field conditions.

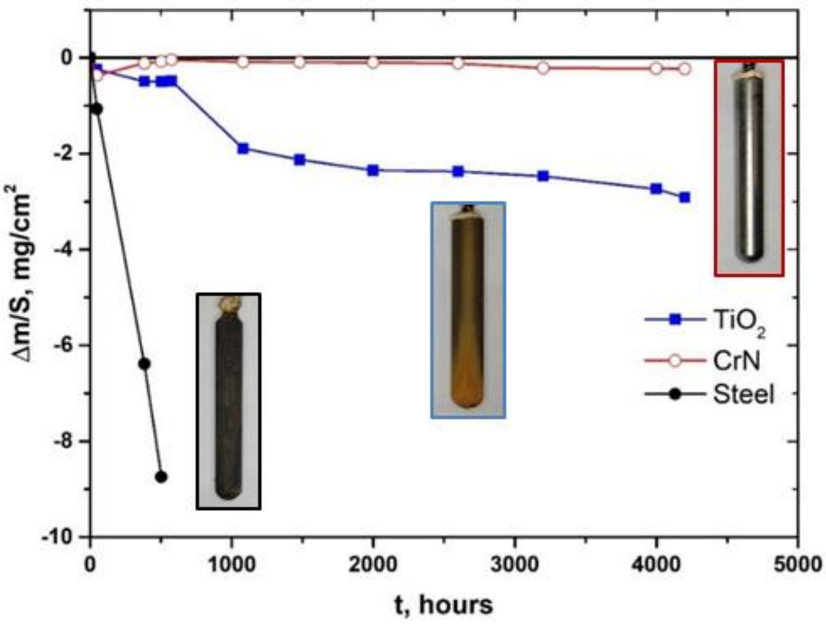

Figure 4: Weight change of bare and coated steel samples (with TiO_2 or CrN) as a function of the time spent in distilled water at 90 °C (EURAD ConCorD WP 15 MS329, 2024)

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

At KIPT, deposition of coatings including metallic, ceramic and composites of those such as CrN/CrON, Ti/TiO_2, Ti/Cu and associated potential multilayers on steel substrates by cathodic arc evaporation is considered, both in terms of adhesion and of corrosion resistance as compared to the metallic substrate.

2.2.3 Spray deposition methods

Spray deposition methods are a type of solid-state deposition processes in which powdered particles are accelerated at supersonic velocities through a nozzle by a high-pressure gas (e.g., nitrogen or helium) and are deposited onto the substrate through plastic deformation. Thermal spraying methods, like detonation gun (D-gun) or High Velocity Oxy-Fuel (HVOF) involve the melting of the powder particles, in contrast to cold spray deposition. This major difference leads to specific features of the corresponding coatings, as shown below, but a common advantage to both ones is the possibility to achieve millimetre to centimetre layer thicknesses.

It has been reported that Cold Spray Coatings (CSC) exhibit advantages for covering nuclear waste containers, where maintaining the integrity of the underlying material is critical for long-term durability (Ross *et al.*, 2022; Irissou *et al.*, 2022), and the limitation of drawbacks like oxidation (if an inert transport gas is used), thermal stresses, and phase transformations in the substrate is no stranger to this finding. It can be noted that the quality of coatings (density, absence of porosity) contributes to an increase in both the mechanical and resistance to corrosion properties. This quality is strongly dependent on the CSC process parameters. Cold sprayed copper coatings would provide an excellent protection against pitting and general corrosion as the corrosion behaviour of both Cu cold spray coating and commercial wrought Cu is similar (Partovi-Nia *et al.*, 2015; Yeom *et al.*, 2021; Guo *et al.*, 2022). An annealing after deposition is beneficial for improved microstructural and mechanical homogeneity (Zheng *et al.*, 2025). Cold spray of Zn-Al coatings as sacrificial coatings was also studied as an additional protection for disposal containers against corrosion. Whatever the composition of the coating, the protection was maintained, with the 15 wt.% Al coating giving the best performance (Martin *et al.*, 2024). Addition of ceramic powder to the metal (called CerMet) would increase the coating adhesion and density. It improves mechanical properties and corrosion resistance in comparison to the cold spray deposits of the pure metal without ceramic inclusions (Jose *et al.*, 2024). In the case of Cu-Al_2O_3 cermet, the addition of Ni in the Cu-Al_2O_3 improves the corrosion resistance (Zhang, L. *et al.*, 2019).

Thermal spray coatings (TSC) generally exhibit a very low porosity, which is mandatory for the application here considered. Depending on the spray technique, other advantages can be pointed out, like easiness to cover large pieces for arc wire spray, excellent adhesion to substrate for HVOF, etc. In 2004, a research work was published that dealt with some alumina-based ceramic coatings deposited by several spraying techniques as potential corrosion barriers for the steel of the disposal waste containers (Haslam *et al.*, 2005). The results showed that some coatings have demonstrated superior corrosion protection for the plain carbon steel substrate; in particular, the HVOF and D-Gun thermal spray processes produced coatings with low connected porosity, which limited the growth rate of corrosion products. It was also demonstrated that these coatings resisted spallation even when an intentional water flaw was applied that allowed for corrosion of the carbon steel substrate underneath the ceramic coating. Alumina-based thermal spray coatings, and more precisely Al_2O_3-TiO_2 oxide ceramic coatings, are also considered as corrosion protection for carbon steel pipes for petroleum industry (Zavareh *et al.*, 2015). Similarly, also for protecting oil pipes, Cr_3C_2–NiCr films deposited onto carbon steel using HVOF have shown good wear resistance and prevented seawater to attack the substrate.

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At EMSE, composite Cu+30w%Al_2O_3 cold spray coatings are applied to carbon steel cylinders of grade E220 with a diameter of 40 mm. Then, a thermal treatment is performed after deposition to improve the quality of these deposits and, notably, their tensile mechanical strength. Indeed, an annealing can lead to microstructural changes of the composite Cu/Al_2O_3 coatings, both by increasing grain size and by promoting diffusion of material between the copper particles, allowing the interparticle boundaries to be "erased".

To study corrosion, conventional electrochemical techniques such as corrosion potential monitoring and polarisation curves are used under conditions approaching the temperature and chemical composition of groundwater. Very low scan rate linear voltammetry (below 1 mV/s) is applied. The corrosion rates are also estimated by mass loss of samples exposed for several months to these environmental conditions. The chosen test aqueous solution is an aggressive synthetic groundwater, and its temperature is 90 °C. Stress corrosion is also conducted using a setup installed on a tensile testing machine, allowing for tests at low strain rates and/or constant load to study creep and the effects of corrosion on creep rate.

2.2.4 Electrodeposition

Electrodeposition (or electroplating) involves the electrochemical reduction of metal ions from a solution onto the metal surface to be treated. It results in the formation of a solid metal or alloy coating. Originally, electroplating has been a suitable process for the deposition of thin-deposited layers (thickness up to 100 µm). Despite Cu deposition up to 20 mm thickness is commercially available, the main challenge of electroforming is to control the high surface roughness when deposition thicknesses are larger than hundred micrometres, due to the high current density on edges and co-deposition of impurities while electroforming (Fallah *et al.*, 2021; Jung *et al.*, 2015). Note that copper deposited by electrodeposition has been studied for 10 years in Canada (Keech *et al.*, 2014; Poles, 2024). As the electroplating process typically involves the immersion of the substrate into the plating bath, hydrogen from the water may enter the surface of the substrate during the process. There is hence a risk of hydrogen embrittlement during the electroplating process, which can compromise the mechanical properties of the substrate. Implementing measures to mitigate this risk is essential (Williams *et al.*, 2024).

It can be noted that despite copper is the material of choice for the application, other metals such as Ni and/or Cr would require evaluation as potential protective materials of the container (Okonkwo *et al.*, 2022). The interest to explore other materials is first the evaluation of protective behaviour, second, for economic, environmental and availability aspects. Functionalisation of the electroplated surface would be beneficial to lower corrosion (Mousavi *et al.*, 2021) by realising superhydrophobic surface.

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

At University of Warsaw, electrochemical deposition of protective coatings with selected composition on substrates delivered by project partners is carried out. The coatings include copper and Cu-rich alloys with Ni and/or Sn, and Ni-rich alloys with e.g. Cr and/or Zn with selected varying content. An analysis of electrochemical properties/stability of the coatings is addressed in terms of corrosion behaviour. Electrochemical tests include EIS under open circuit and polarisation conditions, corrosion tests (polarisation curves), general electrochemical evaluation, OCP measurements, hydrogen uptake analysis.

2.2.5 Arc fusion welding

Arc fusion welding refers to a group of welding techniques that use an electric arc to melt and join metals. In nuclear waste management applications, the primary arc fusion welding techniques include Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), and Plasma Arc Welding (PAW). A critical review of welding technology for canisters for disposal of SNF and HLW was produced by Nagra in 2010 (Pike *et al*., 2010).

These welding techniques are critical in the fabrication and sealing of nuclear waste containers, ensuring both structural integrity and containment of hasardous materials. GTAW, known for its precision and control, is often used for high-quality welds, particularly in the handling of stainless steel and other metals commonly used for nuclear waste containers. GMAW, with higher deposition rates, is employed for faster welding processes, making it suitable for thicker materials. PAW, on another side, offers deep penetration and higher energy density, which is ideal for applications requiring robust and durable welds.

The quality of welds is of paramount importance, as they must withstand stress and maintain integrity, similarly to the container material itself. The choice of arc fusion welding technique depends on the specific material, the container design, and the operational requirements, with each technique providing unique benefits to ensure the safe storage, transportation and disposal of nuclear waste. In the welding area, hardness values in the fusion zone (FZ) and heat-affected zone (HAZ) are slightly higher than that of the base metal (Tang *et al.*, 2024).

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

At LUH, welding experiments focus on the investigation on welding concepts in order to obtain narrow gap welding of thick materials in implementing different welding technics (TIG/GMAW/SAW and RES) as potential methods. Metallurgical properties of the welded zone will be characterised, that includes grain size distributions, phases and precipitates, porosity and cracks that can locally change strength and ductility. Corrosion properties are investigated in open circuit potential in comparison to the base metal, and corrosion current density measurements will allow to evaluate pitting corrosion potential. Materials and conditions of interest for various partners in relation with a DGR concept will be considered.

2.3 Life Cycle Assessment and Life Cycle Costing

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are critical methodologies used to evaluate the environmental and economic impacts associated with the entire lifecycle of a product or system. In the context of nuclear waste containers, these approaches provide comprehensive insights into the environmental burdens and cost implications throughout the different stages of the container's life. These stages include raw material availability, extraction, manufacturing, use, maintenance, and disposal (Darda *et al.*, 2021, Clayton *et al.*, 2024).

The review of (Clayton *et al.*, 2024) established that the published literature includes few attempts to investigate the environmental impacts of novel treatment conditioning technologies and those in development using LCA methods. Most prior work focuses on efficiencies and effectiveness of application into the current fuel cycle. The environmental considerations are only being incorporated into the development of new technologies via the narrower perspective of site licensing and local regulation rather than via a more holistic, life cycle perspective. This is likely hindering the overall environmental sustainability of the sector and could be rectified by applying early stage or anticipatory LCA techniques to guide technology development in radioactive waste management. With further attempts to collect data on specific waste processing technologies, LCA could be used to provide valuable insight into the most environmentally favourable options within decision-making processes.

Beyond the sole waste management field, research studies embrace a whole industry, for instance the ceramic industry (Monteiro *et al.*, 2022). One of the main outcomes of this work is that the proposed methodological approach (combining LCA and LCC) proves to be useful to compare the environmental and economic benefits of investment decisions and raise industrial confidence in strategies towards carbon neutrality. Any plan for a sustainable development and production of radioactive waste containers within Europe (and beyond) should mandatorily consider this issue.

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

Life cycle assessment (LCA) and life cycle costing (LCC) will be undertaken by SIIEG NASU. The main aims of this work are: (i) to estimate the impacts of innovative processes developed within InCoManD, (ii) compare them, if available, to base case options, and (iii) provide insightful guidance in the selection of those innovative solutions. LCA involves: the quantification of environmental burdens of the container solution via assessment of the energy and materials used and wastes released to the environment; the quantification of environmental impacts (*i.e.*, how burdens translate into actual impact); identification of opportunities for environmental improvements. LCC provides estimates of many sorts of costs that include capital costs, fixed and variable operating costs, recycling costs… For both approaches, the amount of required input data is large, and mostly depends on the DGR concept and even, on the country where the DGF will be operated. Therefore, this data will be collected and used on a couple of the most promising solutions identified within Tasks 3 and 4 of InCoManD.

3. Containers durability: corrosion resistance of established and novel materials

The durability of nuclear waste containers is a key factor in ensuring the long-term safety of a geological disposal facility (GDF). EURAD-2 Work Package 9 InCoManD will provide new insights into the corrosion resistance of both established and novel materials by assessing their behaviour under representative disposal conditions. Experimental and modelling approaches are used to explore the mechanisms of degradation and strategies to improve material stability in extreme environments. This chapter presents the latest findings in this field, principally but not only relying on EURAD-1 WP ConCorD (Abdelouas *et al.*, 2022 and 2024), and provides critical information for the development of more robust and durable containment systems.

3.1 Resistance to chemical attack: effect of solution composition

The effect of the chemical environment on the corrosion of well-established container materials, evaluated in lab-experiments by exposing materials to various solution compositions, has been extensively studied in the past. Recently, within the framework of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024), experimental studies have been conducted to assess the impact of the chemical environment, including the experimental analysis of coupled processes and transient states. Parameters such as temperature, irradiation - and its radiolytic effect on the surrounding water -, and redox potentials have been considered as well (Muñoz *et al.*, 2023 and references therein). In addition, corrosion studies considering groundwaters of diverse salinity, bentonite pore waters or $MgCl_2^-$ and NaCl-rich brines, representative of salt formations, as well as other aggressive chemical environments (Kursten *et al.*, 2003) or cementitious waters (Goethals *et al.*, 2024) were performed.

Studies dealing with the leaching rate of ceramics as materials for waste containers are scarce, and relatively old. One can cite the comprehensive work produced by the Swedish Corrosion Institute in 1980 (Mattsson, 1980). In this report, it is shown that alumina is sensitive to leaching solution essentially for hyper acid and basic solutions at temperatures around 100 °C, with leaching rates reaching 90 µm/yr at pH 14.7 at this high temperature. In neutral water (even at 100 °C), this rate is lower than 1 µm/yr, and it depends on the alumina composition (the purer the compound, the lower the rate). In another study, four ceramic oxides were studied, immersed in deionised distilled water or in synthetic groundwater representative of the Canadian repository concept (Onofrei *et al.*, 1985), under static conditions at 100 °C. The most important result is that the leaching rate strongly depends on the purity but also on the density of the ceramic materials, as well as the composition of the leaching agent. The leaching rates were found to rapidly decrease after a few days, and to be relatively low, in the order of 1 µm/yr. However, this decrease was ascribed to a solubility limit because of the static conditions.

All these results have been later reproduced in a work that did not deal with radioactive waste disposal (Huang *et al.*, 2012). Thus, it is important to emphasise that alumina-based ceramics, and most likely other oxides, could exhibit proper behaviour upon leaching conditions, if those conditions are not extreme (*i.e.*, very low or very high pH, at high temperature).

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

The experiments included in InCoManD regarding chemical resistance are primarily dedicated to assessing the leaching/corrosion resistance of container materials under different simplified chemical conditions. Those plans proposing experiments accounting for specific scenarios are described in the following sections.

CIEMAT investigates the leaching of Al_2O_3 (provided by GALTENCO) in a hyper-alkaline solution at 50 to 80 °C, environments closely representative to the French DGR concept. Static experiments are first conducted to have a crude estimate of the leaching rates and make a first material selection and leaching experiments with a continuous flow of the solution will be subsequently performed, using a dedicated set-up. In addition, sealed alumina coupons implementing the method developed within InCoManD that uses microwaves are also tested.

GNS investigates the corrosion behaviour of nickel-based alloys, corrosion-resistant steels, and copper under bentonite conditions. Experiments simulate disposal environments with bentonite porewater at pH 7.5–8.5, under both aerobic and anaerobic conditions, and with realistic porewater chemistries (including chloride, sulphate, bicarbonate, and sulphide).

SUBATECH analyses the corrosion of several materials prepared by EMSE (steel coated with Cu-Al_2O_3) in bentonite environments and in a controlled humidity environment, prior to gamma irradiation, with oversaturated NaBr (~7M), of NaCl (~7M) or 1.75% w/v NaCl.

University of Warsaw undertakes comparative electrochemical and non-electrochemical corrosion experiments on steel substrates with varying carbon content, including pure Cu, Cu-rich alloys (e.g., Ni, Sn), and Ni-rich alloys (e.g., Cr, Zn). Comparative tests are performed in more concentrated aqueous electrolytes with pH close to the neutral value and also in aqueous acidic or alkaline media (e.g. 0.5 M H_2SO4 and 0.1 M KOH), to test resistance and properties of the selected metal coatings.

3.2 Effect of temperature

Over time, the physicochemical characteristics (e.g. oxygen content, saturation, temperature) in the DGR environment will change. For example, as shown in Figure 5, temperature variations caused by the decay of radionuclides will affect the corrosion of the selected metal containers. An initial oxic and unsaturated phase (stage 2) leads to an anoxic and drier period with higher temperatures (stage 3). In this stage where desiccation of the buffer material occurs, minimal or no corrosion is expected as low water availability limits microbial activity. Eventually, there will be a stage, where anoxic processes with local and uniform corrosion will take place with sustained moderate temperatures (Harper *et al.*, 2024).

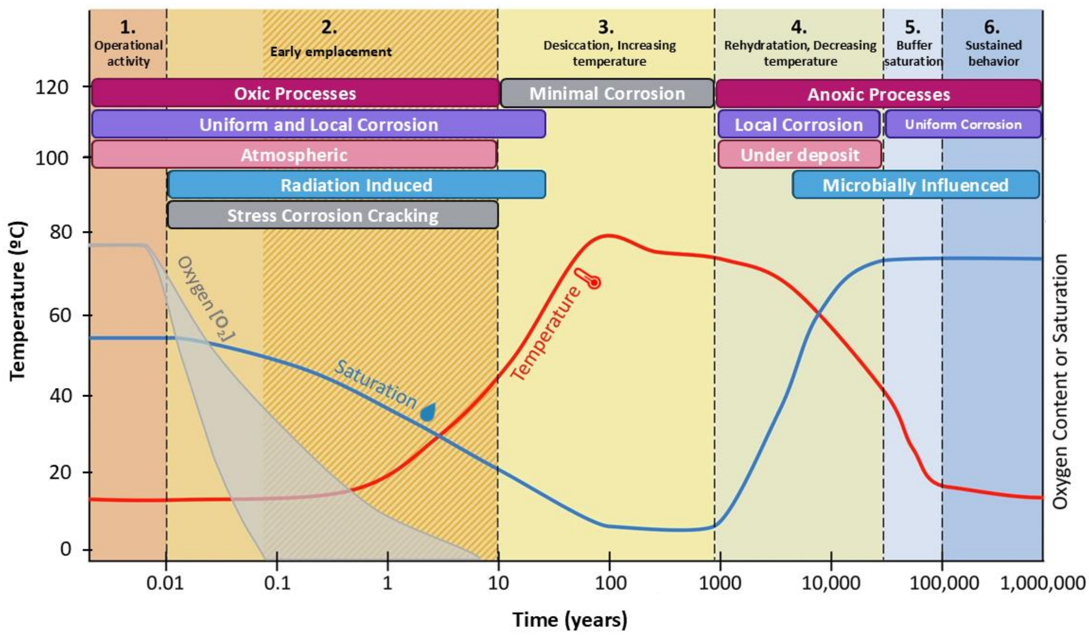

Figure 5: Examples of oxygen, temperature, and saturation variation expected in a DGR environment (modified from Harper et al, 2024).

The effects of thermal cycling have been extensively studied for well-established materials such as carbon steel (C-steel) or copper (Cu). In the case of C-steel, (Senior *et al.*, 2023) investigated the degradation of wires in young cement water (YCW) at high temperature (50 and 80 ºC). At 80 ºC, a higher conversion rate of $Fe(OH)_2$ to magnetite was observed. This corrosion product forms a protective layer that reduces the long-term corrosion rate, whereas at 50 ºC magnetite formation was slower, and the layer formed was more porous and less protective. The latter study is consistent with the research conducted within the Task 5 of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024). As part of the task, CIEMAT performed corrosion tests at 80 ºC on C-steel coupons (Nagra C-steel and Czech C-steel) in contact with different compacted-saturated bentonites (FEBEX, SWy3 and Czech bentonite). The results showed corrosion rates ranging between 28 µm/yr and 413 µm/yr; these rates increased with temperature and pore water salinity, and the highest one (413 µm/yr) was observed for Nagra C-steel in contact with FEBEX bentonite compacted at 1.4g.cm^{-3} (Smart *et al.*, 2024). Moreover, investigations were performed by UJV-Súrao with Czech C-steel in MX-80 Wyoming bentonite at temperatures up to 150 °C. The highest corrosion rate was found for unirradiated samples after 6 months at 150 ºC, with a decreasing rate as the experiment was extended to 18 months (Smart *et al.*, 2024). This agrees with previous studies performed with C-steel where a higher corrosion rate was found at 80 °C at the beginning of the experiment, but greater corrosion decay was observed at higher temperatures (Winsley *et al.*, 2011).

Other iron-based materials showed a higher corrosion rate at high temperatures. For instance, ductile cast iron (GGG40; EN-GJS-400-15) in contact with a slurry of bentonite, hydrated with synthetic Opalinus clay porewater, had a corrosion rate of 6 µm/yr at 30 ºC, while it was twice as much at 50 °C. Another ductile cast iron (namely spheroidal graphite cast iron – SGI), showed that the increment in temperature of 50 °C significantly increased the corrosion rate (Smart *et al.*, 2024). These results are supported by a study (Hesketh *et al.*, 2023) where degradation of iron materials increases with temperature because of a decreased activation barrier, for example for chemical and electrochemical reactions.

Another well-established material is Cu-OFE+P, and several studies have analysed its durability under high temperature, different compaction densities (1.4 g cm^{-3} and 1.6 g cm^{-3}) and fully saturated anoxic conditions. Analysis performed with Cu-OFP coupons in different compacted bentonite samples subjected to convective water-vapour fluxes at 80 ºC by CIEMAT showed corrosion rates ranging from 3 to 9 µm/yr. Mass loss measurements indicated the highest corrosion rates for Cu in contact with Czech bentonite, ranging from 8 to 9 µm/yr. In this case, the corrosion rate was more influenced by the type of bentonite than by the dry density (Smart *et al.*, 2024). Other studies were carried out by (Martinez-Moreno *et al.*, 2023 and 2024) on high-density compacted bentonite blocks (1.7 g/cm^3) with Cu-OFHC) discs. The results showed the precipitation of Cu_xS on the surface of the metal disc at 30 °C, while no precipitates were observed by microscopy after one year of incubation at 60 °C. This supports the hypothesis that higher temperatures reduce the formation of biotic corrosion products such as sulphides due to the limitation of microbial activity. Novel Cu alloys (Copper-nickel alloy - CuNi) were tested at higher temperatures by KIT-INE as part of task 5 of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024). The results showed the presence of Cu(0) and $Ni(OH)_2$ at 50 °C and suggest that at higher temperatures Ni is oxidised to Ni(II) while Cu is not. In addition, other corrosion products as sulphides were detected at 50°C (Smart *et al.*, 2024). Novel Cu-based materials were also recently investigated, that are Cu + 32 vol.% Al_2O_3 composites (copper with embedded alumina particles). Coatings of this composite deposited by cold spray were submitted to electrochemical tests at 90 °C in synthetic groundwater. No significant difference between bulk copper and composite Cu-based deposits was observed (Smart *et al.*, 2024); however, this study could not be performed in a corrosive environment and further investigations are absolutely needed to assess the behaviour of this new material in more realistic conditions. There are materials that are gaining a renewed interest. For instance, titanium (Ti) alloys are materials worth to be considered because of their low density, high strength and ability to withstand extreme temperatures (Zhang, Q. *et al.*, 2019). In another study (Pang & Blackwood, 2016) the corrosion behaviour of titanium alloys over the 60-200 ºC temperature range was analysed. The results showed that both Ti Grade 2 and Grade 5 undergo crevice corrosion at 80 °C and 200 °C, respectively, while Ti Grade 7 shows no corrosion, even at 200 °C, because Pd stabilised the passive TiO_2 film.

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

Experimental plans proposed within InCoManD incorporate elevated temperatures to assess the impact of heat generated by radioactive waste on the corrosion rates of various container materials. These studies aim to simulate more realistic disposal scenarios and to analyse coupled processes that have not been previously explored.

BASE and KIT conduct experiments using environmental AFM to study corrosion on metal coupons (Cu-OFP cast iron with spheroidal graphite, carbon steel, and austenitic stainless steel) in 0.1 M NaCl, anoxic synthetic groundwaters, and bentonite suspensions at room and elevated temperatures (50 °C and higher). Surface evolution is monitored in real-time, with ex situ analysis (SEM-EDXS, XPS) to complement the study. These experiments compare with Materials Corrosion Test (MaCoTe) and In situ Corrosion experiment (IC-A data) at Mont Terri.

SIIEG NASU investigates the near-field evolution of the steel and copper materials in the context with a bentonite buffer, including experiments at elevated temperatures (up to 130 ºC).

ZAG investigates how temperature and oxygen affect the initiation and ending of localised corrosion. To do so, *c*oupled multi-electrode arrays of passive alloys (e.g., AISI 304/316) will be used to study crevice corrosion in NaCl solution under controlled temperatures (RT to ~90 °C) and controlled dissolved oxygen levels. Localised corrosion will initiate under aerated conditions, and it is expected it would come to stop under certain dissolved oxygen level. Currents, temperature, oxygen, and visual data will be monitored, with final micro-CT scan to assess the actual damage.

3.3 Effect of irradiation

Research on the effects of irradiation phenomena, particularly induced by gamma radiation, on the corrosion of metal containers has advanced rapidly in recent decades. The most extensively studied metals remain the primary ones considered in most repository designs, namely C-steel and copper (Abdelouas *et al.*, 2022; Morales-Hidalgo *et al.*, 2024; Fenart *et al.*, 2021). However, literature on emerging materials, such as titanium, metallic alloys, and even more on ceramics, remains limited. For example, when radiation primarily originates from gamma radiation induced by the decay of Cs-137, a fission product with a relatively short 30-year half-life, the radiation intensity rapidly decreases after the repository's closure (Soroka *et al.*, 2021). However, due to its high penetration ability, effects of gamma radiation are crucial to evaluate at various radiation levels. The latest studies conducted within EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) have resulted in new findings summarized below.

Jacobs Company assessed the thickness loss as a measure of the corrosion rate in both copper and C-steel by exposure to a simulated bentonite porewater solution and under varying gamma radiation levels and exposure durations at ambient temperature. One of the key findings was that in tests lasting 5,000 hours or more, gamma radiation at dose rates of 10 Gy/hr or higher (up to 1,000 Gy/hr) significantly accelerated corrosion in C-steel. The formation of corrosion products on the specimen surfaces was primarily influenced by test duration. All specimens exhibited complete coverage with a black corrosion product after more than 1,000 hours, regardless of radiation exposure levels. In tests with shorter term, (< 1,000 h, same dose rate) corrosion appeared as either discontinuous patches of corrosion products or light tarnishing (Bevas *et al.*, 2024). These results suggests that dose rate affects corrosion product chemistry, particularly for carbon steel, and varying the dose rate could impact corrosion in a complex manner, as the corrosion resistance relies on forming a protective film (Bevas *et al.*, 2024). For copper, the key finding was that gamma radiation notably increased the corrosion rate, even at low dose rates. When comparing the corrosion rate under irradiation to that of unirradiated control tests (after 10,000 hours), the corrosion rate was found to rise by a factor of 2 to 60 as the dose rate increased by a factor of 100 from 0.1 to 10 Gy/hr (Smart *et al.*, 2024). When comparing Jacobs' results between the two metals, it was confirmed that C-steel has a significantly higher corrosion rate in unirradiated conditions than copper. However, the relative increase in corrosion rate due to irradiation is much smaller for C-steel compared to copper.

ÚJV also investigated the effect of gamma radiation (dose rate of 0.4 Gy/hr) on C-steel in the presence of bentonite (BCV or MX-80), while applying high temperatures of 90 ºC and 150 ºC (Smart *et al.*, 2024). The results elucidated that the C-steel samples placed in BCV bentonite and heated to 150 °C showed a lower corrosion rate under irradiation compared to the unirradiated samples. The thickness of the corrosion products on the irradiated samples at 150°C indicated that the corrosion rate remained nearly stable over the entire testing period. The same effect was observed at 150 ºC with MX-80 bentonite. However, no significant effect was observed when the MX-80 bentonite was heated to 90 °C.

In another study (Fénart *et al.*, 2021), two carbon steel grades (P285NH and API 5L X65) were tested for up to 18 months at 80 °C in a fully humid environment, with and without irradiation (up to 20 Gy/hr); some samples were partially or fully submerged in a caustic solution. Corrosion behaviour was similar for both steel grades, showing generalized but uneven corrosion across all conditions. Irradiation had no significant impact, except for immersed specimens where it led to the greatest corrosion depths (Fénart *et al.*, 2021). On the other hand, another conclusion regarding gamma radiation (dose rate of 400 Gy/hr) effect was withdrawn by tests performed by Subatech. The tests on carbon steel grade P235GH performed at ambient temperature showed that the presence of oxidising species (OH· radicals or H_2O_2 molecules) generated by water radiolysis can significantly promote iron corrosion, even in deaerated environments. Another key finding was that the corrosion rate is highest at lower relative humidity (RH) levels, such as 63 %, which suggests that factors like RH and radiolysis products play a crucial role in influencing corrosion behaviour (Sarrasin *et al.*, 2024).

As previously mentioned, there is little published literature to date addressing the effect on corrosion rate and form of irradiation on less studied materials such as titanium and Ti alloys. In a recent study (Wei *et al.*, 2021) the cumulative dose effect of the titanium-palladium alloy TA8-1 and pure titanium TA2 under gamma irradiation was investigated, with a focus on geological disposal of nuclear waste. The irradiation experiments were conducted at room temperature using a ^{60}Co gamma source with a dose rate of 5.0 kGy/h for durations of 40, 80, and 160 days. The results indicated that the pH value shifted from alkaline (8.22) to acidic (2.46 for TA8-1 and 2.44 for TA2), whereas the control solution remained alkaline. XRD and SEM-EDS analysis showed that the main corrosion products consist of TiO_2 and TiO, irrespective of the Ti grade. The sample surface was oxidized, causing slight, localised uneven corrosion. All these findings led the authors to conclude that both tested titanium grades are suitable materials for use in radioactive waste containers.

Regarding cast iron coating, a study in task 5 of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) found that the corrosion rate of spheroidal graphite cast iron coatings exposed to a gamma radiation dose rate of 130 kGy/h was five times higher than that observed under the same conditions without radiation. Based on this result, it suggests that spheroidal graphite cast iron coatings are sensitive to radiation, which has a significant impact on the material's corrosion.

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SUBATECH, in collaboration with EMPE, plans experiments, including coated steel substrates with a Cu-Al_2O_3 mixture (32% Al_2O_3) and pure copper samples. Experiments are conducted in two configurations: coupon alone and coupon in contact with bentonite. Samples are irradiated in a cyclotron facility using a 120 TBq 137Cs gamma source at a dose rate of 400 Gy/h, with total doses of 50, 100, 200, and 400 kGy. High-temperature experiments (up to 80°C) are also performed. SUBATECH supports GRS in studying the corrosion resistance of passive metal coatings for containers made from spheroidal graphite (or ductile) cast iron. The coatings are tested in environments consisting of Wyoming bentonite saturated with Opalinus Clay water, with corrosion performance evaluated under gamma radiation.

CIEMAT in collaboration with Andra and GALTENCO, evaluates the durability of Al_2O_3 ceramics by investigating the combined effects of gamma irradiation (10 Gy/h provided by a ^{60}Co source in pool-like facility), hyperalkaline water and temperature, simulating the French disposal conditions. Secondly, experiments with Cu-OFP and carbon steel mimic the metal/bentonite interface without and with unsaturated FEBEX bentonite (60% w.c), under combined thermal (up to 80ºC) and gamma irradiation levels (total accumulated doses of 14 kGy or higher), going far beyond previous studies.

Additionally, UGR in collaboration with CIEMAT and HZDR investigates the effects of gamma irradiation on microbial communities of compacted bentonite and their effect on metal corrosion. Their contributions are further described in Section 3.5.

3.4 Microbial effects in bentonite environments

Microorganisms can accelerate anaerobic corrosion of metallic disposal containers because of their metabolism. During anaerobic corrosion of some container materials hydrogen gas (H_2) can be generated and support microbial activities such as sulphate reduction and acetogenesis contributing to microbiologically influenced corrosion (MIC). Despite bentonite being a key barrier for inhibiting microbial activity, it has been demonstrated that sulphate-reducing bacteria (SRB) are present in host rocks and backfill materials at potential disposal sites (Bagnoud *et al.*, 2016; Matschiavelli *et al.*, 2019). It is therefore essential that the bentonite buffer is optimally selected and designed to control microbial activity (Martinez-Moreno *et al.*, 2023). Different MIC mechanisms, their connection to abiotic reactions under environmental conditions, the interactions of the microorganisms with different metals (iron, aluminium, zinc, titanium, copper) and their effect on the generation of corrosion products are shown in (Xu *et al.*, 2023).

As part of task 4 of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) effects of radiation (total dose of 14 kGy and 28 kGy) on the indigenous bacterial community of FEBEX bentonite were investigated. Results have shown that irradiation at high total doses of gamma radiation affected microbial diversity, favouring the persistence of certain resistant bacterial genera such as *Massilia*, *Acinetobacter* or *Pseudomonas*. Under these conditions, lower copper corrosion indicates that gamma radiation could indirectly inhibit biotic corrosion by negatively impacting the microbiology of bentonite (Smart *et al.*, 2024). Another relevant repository stressor that influences MIC of disposal containers are elevated temperatures. Some thermophilic indigenous bentonite microorganisms can withstand 70 ºC, while 90 °C was identified as limiting microbial survivability in these environments (Bartak *et al.*, 2023). Based on these results it was hypothesised (Bartak *et al.*, 2024) that MIC in the initial phases of the repository is improbable to occur due to the impact of heat and a possible abiotic zone in the bentonite.

These studies concluded that no biofilm formation on the container surface is possible under conditions of high compaction, high temperatures and radiation. Although these results suggest no biofilm formation under the studied conditions, it is crucial to highlight the need for long-term experiments alongside computational modelling predictions. Throughout the repository's lifespan, bacterial activity will fluctuate and is expected to increase in later stages when temperature and radiation levels decrease, an anoxic phase is established, and groundwater infiltration begins. In the early stages, microorganisms may develop resistance mechanisms that enable them to persist in a dormant state during the most challenging years of the repository and later reactivate when conditions become more favourable for growth.

EPFL and HZDR started to investigate how bentonite dry density influences microbial activity using a diffusion cell. Therefore, bentonite samples (MX-80 and Calcigel) were compacted at varying densities and exposed to sulphate and hydrogen-rich synthetic Opalinus clay porewater (Smart *et al.*, 2024). Batch experiments with a bentonite (Calcigel) slurry in synthetic Opalinus clay porewater and cast-iron coupons showed a surface alteration at an early stage and later, a protection of the surface by Ca-containing mineral phases (Smart *et al.*, 2024). The detection of sulphides confirmed the activity of sulphate-reducing bacteria. The low sulphate content of Calcigel and its changes in microbial community structure and activity in the presence of hydrogen make it a suitable material for studying dry density's effect on corrosion.

Many MIC studies have been focused on well-established materials (Cu-OFE+P or C-steel). Studies performed under conditions of the French repository concept (Callovo-Oxfordian (Cox), cement-bentonite, Solution 15') analysed the possible MIC on carbon steel under medium and high temperature conditions (50°C and 80°C). These studies found that the corrosion rate of carbon steel under the stablished conditions remains low and uniform, with no significant influence from microorganisms. The more alkaline cement-grout compositions exhibit lower corrosion rates and limit microbial biomass and diversity, thereby minimizing their potential impact. At 50°C and 80°C, the high alkalinity of the environment also acts as a protective barrier against MIC (Diler *et al.*, 2021, 2023a, 2023b). However, little is known about the impact of bentonite indigenous bacteria on the corrosion of novel materials (new alloys, metal coatings or ceramics). Titanium alloys are supposed to be immune to microbial corrosion (Holdsworth, 2018). In a study (Unsal *et al.*, 2023) Ti coupon resistance against *Desulfovibrio vulgaris* was tested and reported that it resists uniform corrosion with no weight loss after 14 days of incubation. However, this metal is not completely resistant to MIC pitting. Another material under consideration is nickel alloys, which are highly resistant to microbial corrosion, but can be also affected by microbial activity, and further studies are needed to understand their effects (Holdsworth, 2018). To date, the influence of microorganisms on the long-term safety of ceramic containers has not been studied, leaving a gap in the understanding of their impact on stability and durability. For these reasons, the vulnerability of novel materials under DGR conditions should be assessed combined with the development of mathematical models to improve predictions of microbial effects on the DGR.

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EPFL and HZDR undertake laboratory experiments on microbial growth inhibition in bentonite (MX-80, Calcigel) using diffusion reactors with compacted bentonite adapted for microbiological studies developed during EURAD-1 Work Package 15 ConCorD. One key reason is the absence of systematic studies that vary dry density at regular intervals to identify how microbial growth decreases as a function of dry density. Moreover, existing data on the threshold bentonite density that inhibits growth rely on cultivation methods rather than state-of-the-art techniques like DNA quantification. Additionally, the term 'threshold density' encompasses many factors, such as the physical limitation of space and slow substrate diffusion, but the critical factor(s) controlling microbial growth and the underlying mechanisms remain unknown. In addition, at HZDR the MIC on carbon steel via batch experiment in a Calcigel bentonite slurry is investigated.

In-situ experiments are conducted as a part of the Iron-Corrosion Experiment (IC-A) at the Mont Terri URL. This phase of the experiment will target: (1) the role of residual oxygen (O_2) trapped within the bentonite buffer on microbial communities, including potential inhibition of sulphate-reducing bacteria (SRB), corrosion, and the mineralogical and chemical changes in bentonite; (2) the ability of Opalinus Clay porewater populated by up to 40% of SRB, to colonize bentonite, along with the mobility of bacteria within fully saturated bentonite; and (3) the persistence of aerobes in bentonite despite anoxic conditions to better understand microbial survival strategies in the bentonite buffer and the potential impact of aerobes on inhibiting SRB growth.

Partners from Czech Republic (VSCHT/UJV/SURAO/TUL) focus on analysing the container lifetime for the SURAO safety case by studying the mechanical pressure evolution in compacted bentonites due to corrosion product formation and stress raisers. The project examines how corrosion products increase pressure and reduce bentonite porosity, potentially limiting microbial corrosion activity. Experiments use BCV bentonite saturated with artificial pore water and iron powder to simulate corrosion interfaces. Two experiments are conducted: one to measure pressure changes over time and another to study localized corrosion and microbial activity. Sterilized bentonite samples are monitored for pressure and microbial activity over 12 months. The goal is to verify that corrosion product formation leads to pressure buildup and reduced microbial activity. It is also investigated the contribution of corrosion products formation (e.g. iron powder) to the Czech BCV bentonite's swelling pressure. This issue has not been addressed before in the Czech research, and it should lead to the refinement of the bentonite's swelling pressure development while the carbon steel is corroding under the condition of the DGR.

In addition, UGR aims to explore the effects of gamma radiation on bentonite microorganisms simulating container/bentonite interface. Key objectives include determining the survival threshold of microorganisms under radiation, assessing the impact of compaction density, and studying microbial communities in relation to copper corrosion. The experiment includes FEBEX bentonite compacted at two densities, with inserted copper discs. Samples will undergo irradiation (1-7 kGy) at CIEMAT's ^{60}Co irradiation facility and be incubated under anoxic conditions for six months. The study focuses on identifying microbial survival limits and their role in copper corrosion, particularly sulphate-reducing bacteria (SRB), as well as the impact on bentonite properties, in collaboration with CIEMAT. Results will enhance understanding of microbial and geochemical processes.

3.5 Effect of near-field environment

The corrosion behaviour of any container material will be governed by its intrinsic properties but influenced by the physicochemical conditions and specific environmental factors (King & Padovani, 2011). Field conditions are described by several parameters, most of which have been addressed in the previous sections. Yet, the container is necessarily in contact with another material, and this interface plays a crucial role in determining the container behaviour. For example, heterogenous corrosion of C-steel linked to varying saturation levels has been previously detected in different clay and bentonite environments (Zuna *et al.*, 2023). This conclusion was confirmed by experiments conducted in task 5 of EURAD1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024), which has shown that the temperature and the degree of bentonite saturation are the primary factors influencing the corrosion rates of C-steel samples embedded in bentonite (Smart *et al.*, 2024). In general, C-steel corrosion rates increase with temperature and porewater salinity while decreasing with higher dry density. Although no definitive effect of initial humidity on corrosion rates was confirmed, a higher initial humidity in bentonite appeared to have a corrosion-inhibiting effect on the steel. On the other hand, the corrosion rates of Cu-OFE+P samples exposed to identical coupled thermo-hydraulic gradients were considerably lower than those of C-steel under the same conditions. Corrosion levels were influenced more by the type of bentonite used than by its dry density. Another study on spheroidal graphite cast iron (SGI) found that corrosion was more severe when the material was exposed to a bentonite suspension. Regarding CuNi alloys, copper oxides were the predominant secondary phases formed during the corrosion experiments across different experimental conditions. For instance, the addition of sulphide did not have a significant impact. Over the long-term evolution under repository conditions, it is still hypothesized that CuNi will degrade, leading to the formation of Cu-sulphides. These studies, like many others, show that considering the near-field environment is vital in assessing the correct material behaviour in expected field conditions. This near-field environment is here limited to cement and bentonite as the materials in contact with the container or essentially defining the field conditions.

3.5.1 Container - bentonite environment

Within the scope of Task 3 and 5 of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024), CIEMAT conducted experiments to replicate the container/bentonite interface, reflecting a representative repository scenario in its early stages. At this point, the bentonite remains partially unsaturated with water, the accumulated gamma irradiation dose reaches approximately 14 kGy, and the conditions remain oxic. This stage is typically referred to as Phase 2, the oxic unsaturated phase, characterized by oxic and unsaturated conditions. They investigated the corrosion behaviour of copper and C-steel in compacted FEBEX bentonite blocks, considering two different compaction densities (1.4 and 1.6 g/cm^3) and varying degrees of saturation (60% or 100%). Additionally, the samples were subjected to two cumulative radiation doses: 14 kGy and 140 kGy. The results have shown that C-steel samples exposed to gamma radiation exhibited higher corrosion rates, particularly when it was in contact with bentonite at lower compaction density and a greater volume of pore water. Corrosion rates were higher on irradiated samples compared to unirradiated ones. However, no significant differences were observed between samples exposed to 14 kGy and 140 kGy (Sarrasin *et al.*, 2024).

Additional corrosion experiments were conducted by CIEMAT using three types of bentonites, FEBEX, SWy-3, and Czech bentonite, compacted at densities of 1.4 g/cm^3 and 1.6 g/cm^3. The tests were performed under 95-100% relative humidity at 80 °C. Three types of metal coupons were also utilized: reference carbon steel from Nagra, reference copper from SKB, and reference C-steel from SURAO. The samples were placed inside a desiccator containing distilled water and maintains under controlled atmosphere. After 286 days of experimentation, the Nagra C-steel coupons exhibited a greater degree of corrosion when the bentonite had a lower dry density. This effect is attributed to the increased O_2 diffusivity through the pore space. Among the different bentonites, the highest degree of corrosion based on highest mass loss was observed in the C-steel interacting with FEBEX bentonite compacted at 1.4 g/cm^3. This was likely due to the higher salinity of the FEBEX pore water compared to the other bentonites.

Corrosion rates for all coupons tested, ranged from 28 to 413 µm/year, with the lowest rates observed in the bentonites compacted at a higher dry density of 1.6 g/cm^3. Magnetite was the predominant corrosion product identified on the Nagra and Czech C-steel coupons, though other iron oxy-hydroxides, such as hematite, goethite, lepidocrocite, and akageneite, were also detected (Fernández *et al.*, 2024).

Regarding the SKB Cu-OFP coupons, after 326 days of experimentation, the degree of corrosion observed was influenced by the type of bentonite rather than by the dry density (Fernández *et al.*, 2024). The Cu coupon interacting with Czech bentonite exhibited the highest degree of corrosion, with a corrosion rate of 8-9 µm/year. However, the variation in corrosion rates across all bentonites was relatively low, ranging from 3 to 9 µm/year, especially when compared to the corrosion rates observed in bentonites interacting with C-steel coupons. Cuprite (Cu_2O**)** was the dominant corrosion product found, whereas only a minor amount of tenorite (CuO) was observed in interactions with Czech bentonite. At the bentonite/coupon interface, azurite ($Cu_3(CO_3)_2(OH)_2$) was also detected, with malachite ($Cu_2CO_3(OH)_2$) being the most prevalent. It is also important to note that the extent of bentonite alteration at the bentonite/coupon contact was less than 0.5-1 mm in all samples, which was significantly lower than the alteration observed in C-steel coupons. In another study (Martinez-Moreno *et al.*, 2023), FEBEX bentonite was tested under dry, compacted conditions at a density of 1.7 g/cm^3, with each bentonite block containing a pure copper disk and being incubated for one year. The results indicated that copper oxides were the predominant corrosion products. In addition, small amounts of Cu_xS species were detected in the non-tyndallized electron donor/sulphate sample suggesting the early stages of copper surface corrosion. Although present in low concentrations, these species aligned with the experimental conditions, where the addition of electron donors and sulphate was expected to facilitate sulphide compound formation on the metal surface. These findings supported the hypothesis that, under the tested conditions, copper underwent incipient corrosion, potentially affecting its stability and reactivity in similar environments.

Concerning the corrosion of spheroidal graphite cast iron GRS monitored the corrosion in contact with a slurry of Wyoming bentonite and Opalinus Clay porewater over a period of 90 days. After the experiments, the surface chemistry was examined using EDX and XPS. The EDX elemental analysis indicated that the corrosion products were mainly iron oxides combined with silicates. The comparable atomic percentages of Si and Na suggested that the silicates were derived from adhered bentonite particles. This interpretation was further corroborated by the local XPS core-level spectra for Na, Si, and Al. The main corrosion products identified were goethite (FeOOH), green rust $[Fe(II)_3Fe(III)(OH^-)_8]^+ \cdot [Cl^- \cdot n\ H_2O]^-$, Fe_2O_3, and Fe(II) intercalated in bentonite (Fernández *et al.*, 2024).

All these novel findings, most of which originate from task 5 of EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) and are still pending publication, have comforted the key conclusion that corrosion is primarily governed by the composition of the container material and the specific environmental conditions to which the material is exposed.

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Many corrosion experiments during the first phase of InCoManD include the bentonite barrier as part of the experimental scenario, to elucidate relevant corrosion processes affected by the bentonite presence. Most experiments aim to analyse the impact of gamma-irradiation or of microbial communities on container corrosion while including compacted bentonite as a material in contact with the container (Wyoming or FEBEX).

BASE and KIT investigate the corrosion behaviour of oxygen-free copper (Cu-OFP), spheroidal graphite cast iron, low-alloy carbon steel, and austenitic stainless steel, using an electrochemical AFM setup. Wyoming bentonite suspensions, equilibrated with synthetic Opalinus and Grimsel groundwaters under anoxic conditions, replicate repository environments and enable comparison with Swiss in situ experiments (MaCoTe and IC-A). GRS evaluates metal coatings for ductile cast iron containers under similar conditions, using Wyoming bentonite slurry with Opalinus Clay water. The study focuses on corrosion resistance, especially after surface damage, and seek coatings with self-healing properties.

Electrochemical testing, along with gamma irradiation (in collaboration with SUBATECH), is conducted to assess the long-term performance of these materials.

CIEMAT proposes different experiments to analyse the corrosion of such materials in the presence of compacted bentonite (FEBEX and BCV), some of which were installed already in ConCorD – EURAD 1 but will be dismantled after more than 1 year of evolution, or will be initiated in InCoManD WP09, focused on analysing the impact of coupled transients at the metal/bentonite interface, specifically examining Cu-OFP (Swedish GDF concept) and C-steel (Swiss and Spanish GDF concepts) under various conditions. Experiments involve compacted bentonite hydrated under different saturation levels, temperature of up to 80 ºC, thermal gradients, gamma irradiation, and redox evolution. The study aims to address uncertainties in the degradation mechanisms of C-steel, Cu-OFP under conditions typical of the container/bentonite interface. Two types of tests are performed: dynamic infiltration tests, which simulate transient conditions where bentonite is saturated over time, and static experiments to simulate long-term interactions between bentonite and metal coupons under high temperature and anoxic conditions. The selected materials for testing include Nagra C-steel and Cu-OFP, with FEBEX bentonite used for saturation. The results will help to determine corrosion rates, corrosion products, and bentonite evolution.

SIIEG NASU focuses on evaluating the corrosion behaviour of steel and copper in contact with bentonite under conditions representative of a DGR. Autoclave experiments simulate near-field environments at 130 °C and 4–5 atm, exposing polished metal coupons to bentonite interfaces over 6- and 12-month periods. These tests aim to assess the influence of key parameters - such as temperature, pressure, and water chemistry - on corrosion processes and to better understand the mineralization and degradation mechanisms at the metal–bentonite interface. Analytical techniques including SEM/EDX and XRD are used to characterize corrosion products and surface alterations. The study is designed to generate robust data for improving predictive models of container lifetime and to support the Ukrainian national strategy for HLW and SF disposal, contributing to the scientific basis for long-term safety assessments of engineered barrier systems.

Czech partners (VSCHT/SURAO/UJV/TUL), in addition to their microbial-induced corrosion analyses, aim to assess the impact of corrosion products on the swelling pressure of Czech BCV bentonite under DGR conditions. The study focuses on carbon steel containers in contact with BCV bentonite and investigates how corrosion products affect swelling pressure. Experiments use BCV bentonite mixed with iron powder, compacted into cells, and saturated with deaerated BCV pore water.

ZAG plans two activities including bentonite. Activity 1 focuses on studying localized corrosion of copper in contact with compacted bentonite (MX-80 or FEBEX) in collaboration with CIEMAT. The goal is to monitor the development of crevice corrosion under varying oxygen concentrations, particularly as oxygen levels decrease over time in a repository. The experiments use pre-compacted bentonite in a confined enclosure, with copper CMEA surfaces exposed to different oxygen concentrations. The research aims to identify critical oxygen levels for halting or repassivating corrosion. The study is relevant to organizations like SKB and Posiva and addresses gaps in research on localized copper corrosion in bentonite. The experiments could last over a year, with potential challenges in maintaining bentonite saturation and managing electrode sizes.

3.5.2 Container - cement environment

Cement-based materials have been used as a geo-technical barrier to prevent or delay radionuclide migration. Their performance depends on density, thickness and composition. For this reason, cement is another material selected in some repository concepts as backfill material, such as the one in Belgium (ONDRAF-NIRAS), among others. The Belgium Supercontainer concept consists of a prefabricated Portland cement-based buffer that surrounds a C-steel overpack. This material creates highly alkaline conditions (pH ~ 13.6) and protects the metallic container with a passive oxide film, which is expected to result in very low uniform corrosion rates (Gaggiano, 2023).

Another study (Senior *et al.*, 2021) examined the long-term behaviour of C-steel in simulated cementitious environments. The results have shown that C-steel wire in young cement water corrodes rapidly but uniformly at the beginning of the experiment, and the corrosion rate decreases after twelve months of incubation. Corrosion results have shown mainly ferritic(III) corrosion products. The Hungarian repository concept uses C-steel (S235JR) as container material and cement (CEM II/B) as buffer material. Experimental investigations at 80 °C over 12 months have shown uniform corrosion of the C-steel, resulting in rapid passivation. In accordance with prior studies, magnetite was the main corrosion product, suggesting that container passivation under these conditions is a relevant area for future research (Fabian *et al.*, 2023).

Other repository concepts, such as the one developed by Andra, also use cementitious materials. The design of their multi-barrier system model includes the use of glass to vitrify the waste, stainless steel to encapsulate the waste form, C-steel for the container, another C-steel grade as a micro-tunnel steel liner, a cementitious-bentonite grout (CBG) to maintain passivation of the steel, and finally the claystone (Robineau *et al.*, 2021a, 2021b). Results of these two studies showed that no Fe/Mg silicate minerals formed because of glass alteration and C-steel corrosion. The presence of CBG did not inhibit the formation of the amorphous gel layer on the glass surface. It had no direct effect on glass alteration under the studied conditions that were, principally, alkaline (pH 8-10) conditions induced by the CBG, and magnetite was stabilised. This corrosion product may help to reduce the corrosion rate of C-steel under repository conditions by controlling iron release (Carriere *et al.*, 2025). However, a new cementitious material is now considered and investigated, which should allow to maintain for a significant period (to be determined) hyper-alkaline conditions (pH~12.5) and hence, to keep steel in passivating conditions.

These studies are essential for refining predictions of the use of cement in the multi-barrier system performance and refining waste package scale modelling. It emphasises the need for long-term studies and analysis of possible corrosion of novel materials in radioactive waste containers under cement-based repository conditions (Tyupina *et al.*, 2023).

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CIEMAT, in collaboration with Andra and GALENCO, investigates the corrosion behaviour of ceramic materials (Al_2O_3) by investigating the combined effects of gamma irradiation and hyperalkaline water (representative of cement environments relevant for the current French disposal concept).

PSI is investigating corrosion processes at the steel-clay/cement interface, focusing on the impact of backfill on iron oxidation and long-term container integrity using advanced micro-spectroscopic techniques and machine learning-based modelling.

ZAG, in collaboration with Andra, measures in-situ corrosion rates using electrical resistance (ER) sensors in environments relevant to the French disposal concept, to evaluate the corrosion of C-steel (API 5L X65) liners in contact with cementitious grout and local groundwater. After the exposure period (up to a year), the sensors will be analysed using micro-CT, SEM, and EDS. The objective is to assess the reliability and functionality of various ER sensors for measuring corrosion rates under different conditions.

3.6 Planned activities within InCoManD described by material type

To provide the reader an overview of the planned activities within InCoManD to address the issues raised in the above sections and related to materials durability, below is provided a (not exhaustive) list of works to be done by type of material.

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The InCoManD project does not involve a systematic investigation of the influence of material composition on its corrosion resistance, but the experimental plans proposed by the different partners provide comparative corrosion behaviour studies for several candidate container materials, covering metals, metal alloys, coatings and ceramic materials. Materials considered (list not exhaustive) are bulk copper and oxygen-free copper (Cu-OFP), carbon and stainless steel, Cu-based and Ni-based alloys, Al_2O_3, SiC, and coatings of Cu-Al_2O_3, Ti/Cu and Ti/TiO_2, to mention the most probable ones.

Copper and oxygen-free copper (Cu-OFP):

BASE and KIT investigate the corrosion behaviour of Cu-OFP, considering emplacement in clay or crystalline host rocks. CIEMAT also studies the corrosion behaviour of Cu-OFP at the metal/bentonite interface. SIIEG NASU investigates the near-field evolution of Cu in the context of HLW and SF disposal in a host rock with a bentonite buffer. SUBATECH investigates pure copper samples prepared by EMSE in bentonite environments. EPFL and UGR analyse microbial-induced corrosion effects on copper specimens in clay and bentonite environments. ZAG analyses localized corrosion (surface roughening) of copper in compacted bentonite, considering an early oxic repository phase and further transition to anoxic phase.

Carbon steel and stainless steel:

BASE and KIT study the corrosion behaviour of low-alloy carbon steel (P285) and austenitic stainless steel, considering its emplacement in clay or crystalline host rocks. CIEMAT studies the corrosion behaviour of Nagra's reference carbon steel (ASTM A694-08 F65) at the metal/bentonite interface. University of Warsaw conducts corrosion experiments on steel substrates with varying carbon content, focusing on evaluating the electrodeposition fabrication method for coatings.

EPFL, HZDR, and VSCHT/UJV/TUL analyse the corrosion behaviour of different steel materials (EPFL: Nagra C-steel and stainless steel 1.4301 - EN 10 088-3 / DIN 17 440 and 1.4404 - EN 10 088-3 / DIN 17 440; HZDR: carbon steel; VSCHT/UJV/TU: S355J2H+N) including the perspective of microbially-induced corrosion, mainly in clay environments, representative of their national repository concepts. ZAG studies the effect of evolving oxygen on initiation and propagation of localized corrosion of passive 1.4301 stainless steel. PSI provides characterisation support to different partners to investigate the processes occurring at the steel-clay/cement interface.

University of Warsaw conducts corrosion experiments on Cu-rich alloys (e.g., Ni, Sn) and Ni-rich alloys (e.g., Cr, Zn) in order to evaluate the electrodeposition fabrication method for coatings.

Ceramic and metal coatings:

SUBATECH analyses the corrosion of steel coated in bentonite environments. BASE and KIT investigate the corrosion behaviour of cast iron with spheroidal graphite (GJS-400-18U/RT), considering emplacement in clay or crystalline host rocks. GRS in collaboration with KIPT and IW-LUH investigates the corrosion resistance of Ti, Cu, Cr and multilayers of Ti/Cu and Ti/Cr coatings and Al and Ti, on mirror polished spheroidal graphite cast iron in clay- and granite-based disposal concepts, evaluating the behaviour of the base metal in scratches to assist in selecting the best coating materials.

The study of the effect of sealing characteristics on the container's degradation behaviour will not be addressed from fabrication perspective within InCoManD, but the presence of soldered or welded areas in materials is included in a few planned experimental corrosion studies.

BASE and KIT investigate whether welding increases the materials corrosion susceptibility, considering friction stir welding for copper specimens and electron-beam or TIG welding for steels. GNS assesses the short- and long-term corrosion behaviour of various soldered materials which include standard options such as nickel-based alloys (2.4610, 2.4663), different corrosion-resistant steels (e.g., 1.4565, 1.4571, 1.4301), and copper (e.g., CW008A), as well as innovative materials like enamels, under typical conditions to be expected for a German repository in crystalline host rock.

4. Experimental and modelling assessment of degradation mechanisms

The long-term performance of container materials used for the disposal of vitrified HLW or SNF is of utmost importance to ensure the safety of final disposal. Failure of the container can occur under various circumstances, after exceeding a threshold of environmental induced degradation, such as the combination of mechanical and corrosion processes, which can be intensified by the geochemical environment.

One of the key findings from EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) was that long-term container failure is unlikely to result from mechanical or corrosion-related mechanisms alone, but rather from their combined effects (Gaggiano *et al.*, 2024). In other words, mechanical loads and corrosion processes inevitably interact. Mechanical degradation of container materials can occur due to various sources of stress, including residual, lithostatic, or hydrostatic pressures, swelling of bentonite buffer or rock displacements (Gaggiano *et al.*, 2024), and failure of containers because of this load occurs more rapidly due to general corrosion that leads to thinning the container walls (King, 2017).

Geochemical modelling involves the simulation of chemical interactions between the container materials and the surrounding geological media. Key factors considered by the modeller include the groundwater composition, temperature, pH, presence of ions and gases, thermodynamics, kinetic parameters, transport processes, boundaries and reactive transport modelling (RTM) (Deissmann *et al.*, 2021). Multi-scale quantitative models for the chemical evolution at the disposal cell and robust mathematical models have been described and derived, respectively, during EURAD-1 ACED and DONUT projects (WPs 2 and 4) (Deissmann *et al.*, 2021; Prasianakis *et al.*, 2024) and with ConCorD efforts (WP 15) (Gaggiano *et al.*, 2024).

4.1 Experimental approaches

4.1.1 Threshold stress level and environment

Vitrified HLW and SNF disposal containers are typically made of metals such as copper, carbon steel, and stainless steel, which are chosen for their corrosion resistance or mechanical properties. The threshold stress level refers to the *minimum stress required to initiate deformation*, *crack initiation, or time-dependent failure* (e.g., creep, SCC, or hydrogen embrittlement) and varies depending on the material and environmental conditions. Research has shown that these levels are also affected by the microstructure of the material, the presence of residual stresses from welding and machining, and the environmental conditions (presence of e.g., oxygen, hydrogen, chloride, and sulphide ions) (King, 2010b). Determining stresses such as SCC stress intensity factor (K_{ISCC}), creep, tensile, and yield strength, for instance, is relevant to identify conditions under which SCC, creep deformation, hydrogen embrittlement and plastic deformation occur. SCC is one possible degradation mode of container materials and can occur by exposing susceptible material to sufficient tensile stress in a corrosive environment.

The state-of-the-art studies about environments that can promote SCC of steel report two forms of SCC in DGFs in sedimentary rock (King, 2010b): near-neutral pH SCC (NNpH SCC) and high-pH SCC. Near-neutral pH SCC is an example of corrosion fatigue promoted by absorbed hydrogen (Chen, 2016). It occurs in anaerobic dilute bicarbonate solutions with pH 5.5-7.5, causing transgranular cracking in carbon steel under cyclic loading. High-pH SCC occurs in concentrated carbonate/bicarbonate solutions with pH > 9.3 in more aerobic conditions, causing intergranular cracking in passive steel, with crack growth rates increasing exponentially with temperature (King, 2010a and 2010b).

High-pH SCC is an example of a slip-dissolution mechanism involving the periodic rupture of a passive film at the crack tip (Parkins, 2000). Cyclic loading promotes cracking by inducing dynamic crack-tip strain, which ruptures the passive film, a process unlikely to occur in clay host rocks, for example.

Despite the unlikelihood of SCC, indications of crack initiation have been reported for carbon steel grades (P235, P265, P275, P285NH and API 5L X65) exposed to NNpH, although the cracks were often shallow (<200 µm deep) and filled with corrosion products (Didot *et al.*, 2017). The clearest indications of SCC were observed on steels with a banded ferrite-pearlite microstructure, which led the French programme to focus on optimising the steel grade, particularly the microstructure (Crusset *et al.*, 2017). Evidence for crack initiation has been reported in high pH conditions for welded steel using Tungsten Inert Gas (TIG), Electron Beam (EB), and Metal Active Gas (MAG) processes. The parent material was found more susceptible to SCC than the weld metal or heat-affected zone. Post-weld heat treatment is being used to reduce residual tensile stress, although its effectiveness in reducing SCC susceptibility needs further validation (Ogawa *et al.*, 2017).

(Kursten & Gaggiano, 2017) investigated the SCC susceptibility of P355 QL2 carbon steel used in Belgian radioactive waste containers under anoxic conditions. Using slow strain rate tests (SSRT) at 140°C, they examined the impact of sulphide concentrations (up to 15.6 mM S^{2-}) in high-pH concrete porewater. The results showed no significant reduction in mechanical properties (yield strength, ultimate tensile strength, elongation at fracture) between sulphide-containing and sulphide-free environments. Ductility ratios (TTFR, RAR) remained above 0.70, indicating high resistance to SCC, even in welded specimens. Fracture surface analysis confirmed ductile failure with no evidence of SCC, suggesting that under repository conditions, P355 QL2 carbon steel is not susceptible to SCC.

Other steel grades such as P285NH and API 5L X65 were investigated in simulating conditions within HLW repository cells (Bulidon *et al.*, 2020). Electrochemical tests identified critical SCC potential ranges between −0.9 and −0.55 V/SCE, depending on material and environment. Slow strain rate tests (SSRT) and constant load tests showed no SCC initiation under deaerated, high-pH conditions at 90°C. However, localized corrosion and under-deposit corrosion were observed in aerated environments, influencing mechanical failure. The study concludes that SCC risk is minimal for these materials in the repository environment, with corrosion being the primary cause of specimen failure.

Studies with copper-coated nuclear waste containers used in the Canadian concept identified four possible, although unlikely, corrosion mechanisms: (i) oxic corrosion due to trapped oxygen, (ii) radiation-influenced corrosion, (ii) anoxic aqueous corrosion, and (iv) microbiologically influenced corrosion (MIC). The study excludes SCC for the Canadian copper-coated container even under extreme, non-uniform external stresses because the stresses in the copper coating will be exclusively compressive, not tensile, as the mechanical support is provided by the container (Hall *et al.*, 2021).

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Experimental assessment of stress corrosion cracking (SCC) and hydrogen embrittlement in copper and steel container materials used in deep geological repositories, with the goal to generate a quantitative database of threshold stress intensity factor values (K_{ISCC}) in representative environments, is one main objectives of InCoManD. This should allow predicting the maximum allowable external stresses that do not promote crack growth. To achieve this, VTT conducts SCC pre-screening and advanced material characterization, ZAG performs detailed SCC testing on copper alloys with varying hardness, and UPM investigates SCC and hydrogen embrittlement in welded steels across multiple disposal concepts. Experimental methods include slow strain rate tests, electrochemical monitoring, X-ray diffraction, and scanning electron microscopy. The coordinated work of these partners, with input from end users such as Posiva, Andra, and Nagra will provide critical data to define safe operating thresholds for disposal containers in repository environments.

4.1.2 Localized corrosion under realistic conditions

Localized corrosion is a phenomenon normally observed on passivated, corrosion-resistant alloys such as stainless steels, Ni-, and Ti-alloys and on carbon steel and copper only under atypical conditions (King, 2017). Although repository-relevant water chemistries typically induce slow, uniform oxic corrosion in copper and carbon steel, localized corrosion remains under investigation to identify unlikely environmental scenarios that may lead to pitting and the resulting damage (Hall *et al.*, 2021). Localized corrosion of container materials involves the formation of pits and crevices due to environmental factors, that might eventually lead to susceptibility to SCC. Pitting corrosion is a critical degradation mode influenced by the presence of chloride ions and other aggressive species in the groundwater, although high concentrations of chlorides would favour general corrosion over pitting corrosion (Bennett & Gens, 2008). On the other hand, crevice corrosion is strongly controlled by the availability of cathodic current, which is influenced by oxygen diffusion and cathode area (Costa *et al.*, 2023).

It has been found that sulphide can undermine the corrosion resistance of copper even in environments designed to promote passivation. When in contact with borate-buffered aqueous solutions containing sulphide and chloride, sulphide films can be formed at significantly lower potentials compared to oxide films. This means that chloride itself does not initiate pitting under passive conditions, but the presence of sulphide significantly accelerates localized attack by destabilizing the passive film (Guo *et. al*., 2019). Qin et al. (2017) identified specific thresholds for passivity breakdown in copper under nuclear waste repository conditions. They found that a chloride concentration of 0.1 M is critical for inducing passivity breakdown. Additionally, the study showed that at 25 °C, pH 8, the presence of 0.1 M of chloride ions significantly destabilizes the passive film, leading to susceptibility to pitting corrosion. A few threshold values for the corrosion of copper in various environments were identified in a thesis (Daljeet, 2020). The study found that a chloride concentration of 0.1 M is crucial for inducing passivity breakdown. Furthermore, sulphate concentrations above 0.05 M and bicarbonate concentrations of 0.01 M significantly influence corrosion behaviour.

4.1.3 Mechanical-corrosion degradation modes of container materials

In a recent study, the joint mechanical–corrosion degradation modes for carbon steel used in HLW disposal were reviewed (King *et al.*, 2024). The compilation study determined K_{ISCC} for SCC initiation ranging from 100 to 300 MPa√m, depending on environmental conditions. Reactive transport modelling indicates that the near field of a KBS-3 repository behaves as a relatively closed system for ~10^5 years, with minimal renewal of sulphide-producing reactants from the far field. Recent models using Monod kinetics simulate sulphate reduction by SRB in the excavation damaged zone (EDZ), backfill, and host rock, areas where microbial activity is possible. Sulphate and organic matter, primarily from gypsum in the compacted buffer, diffuse outward to these zones, where sulphide is produced and then diffuses back to the container. There, it is consumed through reactions with Fe species, precipitation as mackinawite, or copper corrosion. These models support the use of mass-balance approaches to estimate maximum sulphide production within the near-field system (King *et al.*, 2024).

The closure of investigation holes in an HLW repository focuses on restoring the natural barrier of the host rock to prevent radionuclide migration. Low-permeability materials, such as compacted bentonite blocks, bentonite pellets, and cement-based seals, are used to fill the holes, ensuring minimal water flow. Installation methods include gradual backfilling with swelling bentonite or a combination of cement plugs and bentonite seals for deeper sections. Experimental validation supports that SCC propagation is generally slow under these repository conditions (King *et al.*, 2024).

The degradation of copper, which is frequently employed in the construction of containers, is especially concerning with respect to SCC (King, 2021). The hardness of copper can alter its susceptibility to crack initiation and propagation, with harder materials often exhibiting increased brittleness, making them more prone to SCC under certain conditions. Recent mechanical testing using constant extension rate tests (CERTs) indicates that high chloride concentrations and elevated temperatures promote uniform corrosion and ductile behaviour, reducing SCC susceptibility (Harper *et al.*, 2024).

The SCC propagation rate has been investigated for pure copper alloys in the presence of ammonia with the maximum crack depth increasing from 1.5 µm (Fujimoto *et al.*, 2021).

Slow strain rate tests (SSRTs) showed that thick Cu_2O/sulphide films formed on copper during plastic deformation, leading to tarnish rupture-type SCC. The breakdown of these films resulted in porous CuO deposits. Surface and cross-sectional analyses revealed uniform corrosion films and particulate deposits, with cracks surrounded by Cu_2O and CuO. The study concluded that tensile strain and the bentonite environment induce tarnish rupture-type SCC, with NH_3 enhancing crack propagation but not affecting crack frequency (Fujimoto *et al.*, 2021).

4.1.4 Impact of evolving O_2 and redox conditions on localized corrosion and SCC in nuclear waste disposal environments

Evolving O_2 in nuclear waste disposal environments can occur during the early post-closure phase due to residual air trapped in the repository and the radiolysis of water (King, 2019; Harper *et al.*, 2024). Upon these conditions, radiolysis accelerates pitting and SCC by compromising the protective properties of surface films and interacting with other corrosive agents. For instance, in nitrite solutions, copper with applied potential was influenced by dissolved O_2, because the nitrite affects the ionic conduction mechanism of the surface film. Specimens were polarized for 60 s at potentials between −0.74 and −0.54 V vs. SCE, where pure copper was stable, and then shifted to the target passivation potential range between −0.35 and −0.05 V (Bojinov *et al.*, 2022). The interest in finding the passive range is legitimate, as localized corrosion can only occur on passivated surfaces. Competitive adsorption of nitrite ions on the Cu_2O surface led to an increase in film heterogeneities, which is determining for loss of protective ability. This plays a crucial role in the overall corrosion resistance of the copper film, potentially leading to localized corrosion during the initial oxic conditions of the repository (Bojinov *et al.*, 2022). Later these authors found that in saline groundwater, evolving O_2 and sulphide ions lead to higher corrosion rates and the formation of less protective corrosion products (Bojinov *et al.*, 2024).

Evolving oxygen can also accelerate the de-passivation process and hinder the re-passivation of copper in a borate buffer solution in the presence of sulphide ions (Bojinov *et al.*, 2023); however, O_2 is quickly consumed by reactions with oxidizable minerals and aerobic bacteria *within a few weeks or months of backfilling* (King & Kolář, 2019).

The repository environment can be classified as either reducing or oxidising based on the redox potential. In a reducing environment, the cathodic reaction is dominated by hydrogen discharge, while in an oxidising environment, it is driven by reactions such as the reduction of dissolved oxygen (Reback, 2007). The Swedish program found that carbon steel and cast iron corrode rapidly in anoxic groundwater, with the presence of copper affecting the corrosion films. Introducing steel to the environment quickly reduces redox potential due to oxygen consumption (Smart *et al.*, 2001). The French program found that trapped oxygen leads to aerobic corrosion, forming ferric hydroxide corrosion products. As the environment transitions to anoxic conditions, these ferric products are converted to ferrous (Fe(II)) compounds, and further corrosion results in the formation of magnetite (Fe_3O_4) through the Schikorr reaction. The study reported that the corrosion rate decreases over time, with initial rates as high as 18-29.6 µm/year in 0.1M NaOH at 80 °C, dropping to 0.002 µm/year after 2591 days (Kursten & Druyts, 2015).

Despite its low corrosion rates, AISI 316L stainless steel with a pitting resistance equivalent number (PREN) of 24.9 has shown vulnerability to evolving oxygen in 0.6 M NaCl at 50 ºC, leading to localized acidification and crevice corrosion (Costa *et al.*, 2023). Other variables like groundwater pH and temperature can decrease the oxygen content and alkalinity, fostering an increase in the production of hydrogen gas, which in turn, reduces the free corrosion potential of steel, as verified by the Japanese program of nuclear waste disposal (Fukaya & Akashi, 1999).

The current scientific findings point to the importance of designing repository environments that quickly transition to anoxic conditions in order to mitigate the risk of localised corrosion and SCC (King & Kolář, 2019). The critical period for pitting and SCC is very short-lived, occurring only during the initial oxic phase. Once the environment becomes anoxic, the potential for these localised corrosion processes diminishes. Research has shown, however, that pure copper could experience SCC in anoxic environment at sulphide concentrations of 0.01 mol/L, based on slow strain rate testing (SSRT) in synthetic seawater (Taniguchi & Kawasaki, 2008). Additional work suggested that internal diffusion of sulphide into grain boundaries could contribute to localized attack, but definitive SCC mechanisms remain uncertain (Hedin, 2019). The presence of compacted bentonite buffer appears to limit sulphide transport, reducing the risk of SCC. Thus, while localized corrosion and intergranular attack under high sulphide concentrations are evident, SCC remains an unresolved issue (Hedin, 2019).

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Research efforts during InCoManD will provide a definition of defect acceptance criteria based on mechanical testing of copper and steel as container materials. Specific testing methods will include Slow Strain Rate Test (SSRT), constant load test of pre-cracked specimens, and SCC tests of U-bends in simulated environments. At the moment, most arguments against SCC are qualitative and relate to the absence of a suitable environment for such a corrosion process to occur in a repository. InCoManD will build upon Concord's work, where copper was studied under anoxic conditions at room temperature, simulating the fourth phase of the repository lifecycle. The new focus shifts to the critical early post-closure phase, where evolving oxygen and redox conditions can trigger localized corrosion and SCC. This work will clarify how O_2 consumption influences SCC during the oxic-to-anoxic transition.

<u>Copper containers</u>

VTT conducts SCC pre-screening for copper materials through electrochemical testing, in-situ tensile tests with EBSD mapping, and immersion of U-bend specimens in oxic environments at 90 °C, adding nitrites as an aggressive agent. Autoclave tests will simulate the early-phase canister closure to assess SCC susceptibility of Cu-OFE+P and Cu-HCP in the presence of nitrates and chlorides. This data guides further testing, including slow strain rate (SSRT) and creep experiments on tapered specimens. ZAG follows up VTT work by assessing the effect of copper hardness on SCC using 2–4 cold-worked alloys exposed to two different simulated groundwater environments, while UPM investigates residual stress and cold work using X-ray diffraction.

<u>Steel containers</u>

UPM focuses on the combined effects of mechanical loading, corrosion, and hydrogen embrittlement on steel containers, particularly those used in French, Belgian, Swiss, Czech, and Spanish disposal concepts. Targeted steels include S355J2H+N, P285 NH, and ASTM A694-08 F65. Residual stresses from welding are characterized via X-ray diffraction, followed by SCC testing on pre-cracked SENT specimens in relevant synthetic pore waters (e.g., FEBEX, NNpH, Callovo-Oxfordian, and cementitious).

4.2 Geochemical modelling

Modelling concepts and tools for corrosion and related processes have already been quite extensively captured during EURAD-1 Work Package 15 ConCorD (Abdelouas *et al.*, 2024; Smart *et al.*, 2024). In EURAD-2 Work Package 9 InCoManD, the plan is to add an overview and possible enhancements making the models more realistic and powerful. Recently, a review of corrosion processes modelling related to radioactive waste disposal was published (King *et al.*, 2024), followed by a performance assessment. This comprised both steel and copper as container materials and referred to concepts of national radioactive waste management agencies. The second context for this SotA report is related to archeologic (or natural) analogues for corrosion observation, as a potential source of data in orders of magnitude longer time scales than laboratory experiments, which can support the prediction models' validation.

4.2.1 Geochemical modelling and evaluation of transients

Recent advances in mathematical models to simulate and analyse chemical reactions and transport processes in geological systems have shown that machine learning (ML) offers a powerful tool to enhance computational efficiency. It could be shown that surrogate models using Bayesian Regularized Neural Networks (BRNN) and Quantile Regression Neural Networks (QRNN) can predict geochemical variables with high accuracy while reducing computation time by up to 140 times (Jatnieks *et al.*, 2016). Similarly, the potential of hybrid and physics-informed ML approaches for simulating complex, multiscale processes that arise in a GDR was highlighted (Hu & Pfingsten, 2023). Further it was demonstrated that deep neural networks provide an optimal balance between accuracy and computational efficiency for reactive transport modelling (Laloy, 2019).

The growing complexity of coupled thermal-hydro-mechanical-chemical (T-H-M-C) simulations and multi-physical processes in subsurface environments has led to a strong focus on improving computational efficiency and predictive accuracy (Churakov *et al.*, 2024). ML, combined with surrogate modelling, digital twins, and collaborative platforms, offers promising solutions to address challenges such as multi-scale coupling and model realism, which are often compromised due to computational limitations (Churakov *et al.*, 2024). The use of ML in accelerating computationally intensive simulations (particularly in chemical equilibrium calculations) enables the incorporation of more complex geochemical interactions and transport processes, highlighting the urgent need for expanded multidisciplinary benchmarking initiatives (Bildstein *et al.*, 2021).

Recent benchmarking initiatives for ML in geochemistry have been done in the frame of the DONUT program (Prasianakis *et al.*, 2025). The study evaluated the performance of ML models in accelerating geochemical and reactive transport simulations. Two benchmarks were presented: one focused on cement chemistry and another on uranium sorption in clay minerals. High-quality chemical equilibrium datasets were generated using geochemical speciation codes (PHREEQC, ORCHESTRA, and GEMS) to train ML models. Key results show that ML-based approaches provide significant computational speedups, ranging from one to four orders of magnitude, without compromising accuracy. The comparative performance analysis revealed strengths and limitations of different ML approaches. For example, deep learning methods, particularly fully connected deep neural networks, managed to predict complex geochemical behaviours, especially in highly non-linear systems such as cement hydration. Gaussian processes with active learning were effective in reducing training data requirements while maintaining predictive accuracy. The decision tree-based methods provided interpretable surrogate models with robust performance in simpler geochemical systems, such as uranium sorption. Additionally, random forest classification combined with Gaussian process regression (RF-GP) successfully segmented datasets into sub-geochemical systems, optimizing model training and predictions. However, challenges remain, particularly in handling geochemical systems with multiple mineral phases and solid solutions (Prasianakis *et al.*, 2025).

By incorporating the lattice Boltzmann method at the pore scale, the possibility of capturing the dynamic coupling between geochemical reactions, fluid flow, and evolving material properties could be shown (Patel *et al.*, 2021). This capability can be applied to transient processes, such as the progressive dissolution of cement phases, precipitation of secondary minerals, and changes in porosity and permeability over time (Patel *et al.*, 2021). In another approach, the GEM-Selector geochemical modelling package by improving the GEMS3K numerical kernel (Paul Scherrer Institute, 2025) was enhanced (Kulik *et al.*, 2013). The revised Gibbs energy minimisation algorithm enables efficient simulations of complex geochemical systems with multiple non-ideal solution phases. The updated GEMS3K code offers high computational speed, robust mass balance accuracy, and numerical stability, making it suitable for integration into reactive mass transport simulations like the OpenGeoSys-GEMS framework, thus facilitating precise modelling of fluid–rock interactions in subsurface environments (Kulik *et al.*, 2013).

4.2.2 Reactive transport modelling

Chemical reactions and the movement of contaminants in geological systems can change significantly over time, affecting the long-term safety and performance of waste disposal sites. Reactive transport modelling was used to investigate the interactions between iron and bentonite in the Full-scale Engineered Barriers Experiment (FEBEX) in situ test. These simulations revealed that iron corrosion leads to the formation of magnetite and siderite, causing a localised increase in pH and a decrease in porosity near the iron-bentonite interface (Kiczka *et al.*, 2024). Similarly, simulations of the long-term geochemical evolution of an HLW repository in granite have been conducted (Samper *et al.*, 2024a). Interactions between thermal, hydrological, and chemical processes, including mineral dissolution, precipitation, and changes in porosity and permeability, were accounted for in the model.

Specific extensions or alternatives to common geochemical models in equivalent continuum were developed, that include: reactive transport coupled with multiphase flow (changing gas and water saturation) (Samper *et al.*, 2024b), thermodynamic consistent model (Cances *et al.*, 2023), pore-scale and multi-scale models focusing on porosity changes from precipitation/dissolution, also potentially relevant for corrosion products (Yang *et al.*, 2024; Lönartz *et al.*, 2023), application of phase-field models mainly for capturing local corrosion (Martínez-Pañeda, 2024; Mollaali *et al.*, 2025), application of machine learning for acceleration of computing (Prasianakis *et al.*, 2020).

Key findings of the EURAD 1, ConCorD Synthesis Report (Abdelouas *et al.*, 2024; Smart *et al.*, 2024) mention that corrosion rates of iron-based materials, including spheroidal graphite cast iron (SGI) and carbon steel, are highly dependent on environmental conditions. Experimental results demonstrate that the presence of hematite can retard the formation of Fe(II)-bearing protective layers, potentially accelerating corrosion rates. Corrosion progression is further influenced by temperature, with higher temperatures (50 °C) leading to increased corrosion rates, in agreement with previous studies (Hesketh *et al.*, 2023). Additionally, the study finds that Fe(II) formation during corrosion can interact with bentonite, potentially reducing structural Fe(III) or leading to mixed Fe(II)/Fe(III) phases. The findings align with Pourbaix diagram predictions, suggesting that under reducing conditions, sulphide corrosion products are more stable (Abdelouas *et al.*, 2024; Smart *et al.*, 2024). Challenges in reactive transport modelling, such as accurately representing porosity alterations due to mineral dissolution and precipitation, and their subsequent impact on diffusion rates have been identified (Jenni *et al.*, 2024). Although advances were made in questions related to porosity evolution and clogging in highly reactive geochemical systems, there is a need for more advanced modelling to predict coupled processes. The COMSOL multiphysics platform represents an alternative (COMSOL, 2025). For example, complex interactions between dual porosity structures of bentonite considering chemical reactions and transport phenomena were studied for MX-80 bentonite providing satisfactory results, and enhancing the understanding of diffusive ion transport, mineral dissolution, and cation exchange processes (Cabrera *et al.*, 2024).

Unlike traditional models, a novel reactive-transport framework developed (Mundra *et al.*, 2025) treats redox kinetics and transport as transient phenomena, decoupled from Gibbs free energy minimisation. The approach allows for accurate predictions of speciation and precipitation across oxidation states. Case studies on manganese speciation in natural waters and the fate of dissolved iron in aqueous/porous media demonstrate the framework's versatility and its enhanced capability to model multiple redox state interactions in aqueous systems (Mundra *et al.*, 2025).

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TUL, Uni Bern, PSI, and Nagra are developing advanced computational tools to support container design and long-term performance assessments. Machine learning methods will be implemented to improve computational efficiency and predictive accuracy. These models will simulate chemical interactions between container materials and surrounding geological media to capture coupled processes and enhance the realism of long-term safety evaluations.

4.2.3 Correlation between container strength, corrosion reactions and pressure changes

Corrosion-induced wall thinning reduces the container's structural integrity, and pressure fluctuations may cause a plastic collapse. In contrast, passive alloys like stainless steel, Ni-based, and Ti-based materials can experience pitting or crevice corrosion, due to through-wall penetration. This localized attack could result in failure before the container reaches the point of plastic collapse (King, 2017). Recent studies (Koloma *et al.*, 2024; Mukhtar *et al.*, 2024) present findings from a Czech project on iron artefacts buried in soil with limited oxygen. They analysed hundreds of samples from 16 sites with clay soils and maximum waterlogging. Corrosion rates (CR) values range from 0.4 to 4.6 µm/y and vary based on environmental conditions, with anaerobic sites forming siderite, while oxygen-exposed sites favoured hematite and lepidocrocite.

The results showed that even minimal oxygen presence shifts corrosion products from carbonates to oxides/hydroxides like goethite and magnetite (Mukhtar *et al.*, 2024). Previous studies on archaeological analogues for container life prediction (Smart & Adams, 2006) lacked detailed data on corrosion products due to the non-destructive analysis of culturally valuable objects. Consequently, they concluded that, yet corrosion of iron is common and slow, the data available for numerical modelling is limited. Recent studies with significant connections between observed data and modelling (King *et al.*, 2023) evaluated the potential to support the safety case by considering kinetic versus thermodynamic stability to explain the persistence of archaeological analogues. Furthermore, the composition and structure of corrosion products on a Roman artifact, using thermodynamic modelling to interpret and reconstruct the varying environmental conditions for corrosion has been analysed (Valbi *et al.*, 2024).

Other modelling concepts, not primarily related to nuclear waste disposal, have been performed, integrating experimental and computational methods. For instance, the relationship between the hardness and Young's modulus of corrosion products, capturing their evolution over time and considering the cohesion between different corrosion layers was evaluated (Dehoux *et al*., 2015). The in-situ Young's modulus of steel rust was estimated using a thick-wall cylinder model for stress calculation (Liu & Su, 2018). Experiments were conducted with corroded sintered iron, obtaining larger-volume porous blocks containing corrosion products suitable for standard mechanical tests to measure elastic constants (Kupkova *et al.*, 2017). Nanoindentation was used to derive a corrosion expansion formula, contributing to prediction and mitigation strategies (Du *et al.*, 2023). Microstructural and micromechanical analyses of corrosion products were performed, relating Young's modulus and nano-hardness to porosity and grain size (Jiang *et al.*, 2023). A phase-field model incorporating stresses in the corrosion product layer was employed, allowing comprehensive simulation of corrosion with mechanical effects (Martínez-Pañeda, 2024). A custom Python code of cellular automaton coupled with ABAQUS for mechanical calculations was used to capture pitting corrosion (Wang & Shi, 2024). Similarly, the stress field in steel circular hollow sections affected by corrosion was calculated (Zhao *et al.*, 2024).

A specific experiment by SKB (Smart *et al.*, 2006a) focused on corrosion product expansion, where a pile of iron discs was corroded, including contact areas. No significant deformation or pressure increase was observed, which was attributed to different moisture and temperature conditions, leading to softer corrosion products compared to iron in concrete structures.

Copper corrosion in bentonite-enriched environments has been investigated using the point defect model. The results indicate that rock permeability adjacent to the clay backfill influences biogeochemical processes and subsequent copper corrosion rates, revealing that bentonite affects copper corrosion resistance through various mechanisms, including Donnan exclusion and cation adsorption (Ning *et al.*, 2024). By modelling bi-sulphide transport through highly compacted bentonite in a DGR it was found that geochemical reactions, such as the formation of iron sulphide (FeS) and HS^- adsorption, as well as anion exclusion effects retard HS^- migration from approximately 50 to 800 years due to FeS formation or adsorption (Asad *et al.*, 2024). However, these delays are minimal relative to the repository's intended lifespan of one million years, suggesting a limited impact on long-term copper corrosion.

TO BE DONE WITHIN EURAD-2 Work Package 9 InCoManD

TUL, UniBern, PSI and Nagra work together to support the optimization of container design and the understanding of long-term degradation processes in deep geological repositories.

Nagra leads structural assessments to optimize the wall thickness of its traditional carbon steel container, using Ansys software to reduce conservatism while ensuring mechanical integrity under repository conditions (in collaboration with EPFL, with potential contributions from ZAG and UPM).

Uni Bern develops advanced reactive transport models to simulate microbial activity, corrosion, and solute transport in bentonite and clay environments. These models, informed by experimental data and enhanced with dual porosity and two-phase flow features, aim to support design optimization of steel containers under evolving geochemical conditions (in collaboration with EPFL and Nagra).

TUL enhances reactive transport models to include corrosion-driven interface changes and microbial effects specific to Czech materials, while also modelling corrosion-induced stress and deformation in containers exposed to bentonite swelling (in collaboration with Nagra and Uni Bern).

PSI investigates the corrosion behaviour of iron/steel containers at clay and cement interfaces using high-resolution micro-spectroscopic techniques. Experimental data feed into geochemical models built in GEMS, with machine learning applied to accelerate simulations. PSI's work supports long-term container integrity assessments (in collaboration with Nagra, EPFL, TUL, and Uni Bern).

5. Summary

Containers for the disposal of heat generating waste to be disposed of in a geological disposal facility (GDF) represent an essential technical barrier in any multi-barrier safety approach of a deep geological repository (DGR) concept. These containers will be subjected to severe and various challenges, with corrosion resistance being one of the most critical as it governs for a large part the container lifetime. Therefore, it is mandatory to conduct research work on the durability of the container materials in order to assess their stability over a period that can last from hundreds to hundreds of thousands of years, depending on the repository concept. In parallel to national programmes dealing with this very topic, the EURAD initiative tackled this issue, and in particular, the EURAD-1 Work Package 15 ConCorD (2021-2024).

In the current document, it is provided the state-of-the-art at the end of EURAD-1 Work Package 15 ConCorD on (i) the behaviour, as determined by experiments, in selected field conditions of several container materials (such as copper, carbon steel, SiC for instance), (ii) the feasibility and effects of manufacturing processes such as sealing methods, and (iii) the modelling tools available to simulate the complex environment that constitute the multi-barrier system inherent to any DGR concept.

In chapter 2, recent achievements with respect to bulk ceramic-based HLW disposal containers are summarised. It is also highlighted several still existing challenges for these new and innovative container concepts such as effective sealing and mechanical resistance of ceramic materials, to cite the most crucial ones. These issues will be tackled within InCoManD, with alumina-based and SiC-based bulk container materials on the one side, and metallic (Cu, Ti-based) or ceramic (CrN, alumina) coatings on the other side. Several joining techniques for metals and ceramics will also be investigated. At the very end of the project, Life Cycle Assessment and Life Cycle Costing (LCA/LCC) approaches, tentatively addressed in chapter 2, will be further considered within InCoManD.

In chapter 3, the existing knowledge regarding the evaluation of containers durability of well-established materials is summarised. In this respect, environmental aspects like solution composition, temperature, redox conditions, irradiation, microbial effects and container near-field environment (e.g., bentonite, cement) are addressed. Within InCoManD, several experimental approaches are foreseen to further close existing knowledge gaps especially regarding innovative container materials and to enable more reliable predictions about the container's long-term resistance under more realistic (*i.e.*, coupling several degradation parameters) field conditions in DGR environments.

In chapter 4, the need for a holistic approach to understand container degradation is highlighted, considering joint mechanical and environmental factors, as it is clearly demonstrated that neither the corrosion nor the mechanical loads alone allow for assessing the long-term durability of the containers. InCoManD will build a database of threshold stress levels and environmental conditions that can initiate degradation. Copper and steel will be tested under realistic conditions to study the effects of material properties and oxygen on pitting and SCC and machine learning will be employed to improve the accuracy and efficiency of long-term degradation modelling.

In the current document, a brief workplan description is also provided about the EURAD-2 Work Package 9 InCoManD, which stands for *Innovative and new container/canister materials under disposal field conditions: Manufacturing feasibility and improved Durability.* This project aims to deepen further the knowledge for both traditional and novel material's long-term durability under - as realistic as possible – disposal field conditions. New experimental investigations, gained results, and data shall help to improve numerical simulation and extrapolation tools and shall promote to identify and qualify promising novel materials and material combinations (coatings) for SNF and HLW disposal containers.

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