3.2.3 "Containers using advanced materials (Novel Containers)", Domain Insight

Authors: Roberto GAGGIANO; Nikitas DIOMIDIS

Reviewers: Christiane STEPHAN-SCHERB, Patrick GANSTER, Cédric BOSCH, Aurélien DEBELLE, Maximilian MILDEBRATH

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Overview

The waste container is an essential part of the multibarrier systems designed for deep geological disposal. After emplacement in a deep underground repository, canisters will be exposed to the repository environment and its evolution in time. Assuming the nuclear waste repository remains undisturbed (i.e., there are no earthquakes, human intrusion or related phenomena), the only mechanisms by which radionuclides could reach the biosphere is by the dissolution of the waste in the groundwater followed by migration of radionuclides to the surface, or by transport of volatile radionuclides in the gas phase. Consequently, one of the major factors in selecting a container solution for disposal in an underground repository is its resistance to degradation by groundwater that may eventually penetrate the repository environment. Following disposal, resistance to environmental damage processes, including all relevant corrosion mechanisms, is therefore important (Holdsworth 2013). Currently, steels and copper are the materials proposed for adoption worldwide as nuclear waste disposal canister materials. The accurate prediction of the lifetime of the waste container represents an important input for the safety assessment of the disposal system. This requires a good understanding of the corrosion/leaching behaviour of the canister material over periods of thousands to hundreds of thousands of years. This mechanistic understanding may come from existing information in the literature, from new experimental studies or from numerical models. Advanced material options are of interest due to their potential for optimisation. For example, they could offer longer canister lifetimes, more accurate and robust long-term prediction, advantages related to a reduced impact on the engineered and geological barriers or related to manufacturing.

To satisfy the safety requirements and to have the potential for optimisation of container performance, both the choice of the material and of the production route for the canister are very important. Recent developments (e.g., copper coatings) considered in Canada and investigated in Switzerland (Holdsworth 2018), France and Japan have demonstrated that container optimisation is indeed possible and of value to the radioactive waste disposal community.

A number of materials is currently considered for novel containers, both for the production of single material containers (such as alumina (Al_2O_3)-based compounds, silicon carbide (SiC), titanium, nickel, copper) or for coated containers (such as titanium oxide (TiO_2)-based coatings, chromium nitride (CrN) coatings, copper and Cu/Al_2O_3 composite coatings) (Baroux 2016, Holdsworth 2013, Holdsworth 2014, Holdsworth 2018). Even though oxygen free phosphorus-doped copper (OFP-Cu) has been widely studied as canister material (making it a traditional container material), quite an effort is currently being made to optimise the long-term performances of bulk copper under repository conditions, opening the way to alternative copper alloys, other than OFP-Cu, as bulk materials for the production of novel canisters.

Keywords

Novel containers, advanced materials, containment, environmental damage, corrosion, mechanical integrity, ceramics, alumina, silicon carbide, titanium, nickel, copper, titanium oxide, chromium nitride

Key Acronyms

Engineered Barrier System: EBS

Deep Geological Repository: DGR

Stress-corrosion cracking: SCC

Hydrogen-induced cracking HIC

Microbially Induced Corrosion: MIC

1. Typical overall goals and activities in the domain of Containers using advanced materials (Novel Containers)

This section provides the overall goal for this domain, extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to phase of implementation, needed to achieve the domain goal. Activities are generic and are common to most geological disposal programmes.

Domain Goal	
3.2.3 - Containers using advanced materials (Novel Containers). Identify container materials and designs for each wasteform under storage and disposal conditions and confirm properties, behaviour and evolution under storage and disposal conditions.	
Domain Activities	
Phase 1: Programme Initiation	Establish high-level requirements for the canister material, definition of the expected environmental conditions that will pertain at the outer surface of the canister. Assessment of the compatibility of the canister materials with the engineered and natural barriers. Preliminary assessment of the canister production routes and the expected canister lifetime for the different advanced material options: general and localised corrosion behaviour, hydrogen gas generation, mechanical resistance under the expected stresses.
Phase 2: DGR Site Identification	Update the expected environmental conditions that will pertain at the outer surface of the canister. Update the expected canister lifetime for the different advanced material options based on the site-related environmental conditions. Manage iterative review and update the requirements to respond to latest design developments.
Phase 3: DGR Site Characterisation	Perform studies on the impact of the site environmental conditions on the repository environment and update of the environmental conditions at the outer surface of the canister. Verify the impact on the canister lifetime assessment for the different material options. Selection of the material solution(s) for implementation in the next phase.
Phase 4: DGR Construction	Confirmation of the corrosion and mechanical performance of the selected advanced material option(s) under the expected repository conditions to support repository licence application. Industrialise the canister production and transport.
Phase 5: DGR Operation and Closure	Confirm and preserve documentation for the emplaced canisters for licence application for operation/closure.

2. Contribution to generic safety functions and implementation goals

This section describes how Novel Containers (and the associated information, data, and knowledge) contribute to high level disposal system requirements using EURAD Roadmap Generic Safety and Implementation Goals (see, Domain 7.1.1 Safety Requirements). It further illustrates, in a generic way, how such safety functions and implementation goals are fulfilled. It is recognised that the various national disposal programmes adopt different approaches to how disposal system requirements are specified and organised. Each programme must develop its own requirements, to suit national boundary conditions (national regulations, different spent fuel types, different packaging concept options, different host rock environment, etc.). The generic safety functions and implementation goals developed by EURAD and used below are therefore a guide to programmes on the broad types of requirements that are considered, and are not specific or derived from one programme, or for one specific disposal concept.

2.1 Features, characteristics, or properties of Novel Containers that contribute to achieving storage safety as well as long-term safety of the disposal system

2.1.1 Primary goal - relied upon for long-term repository safety

NOVEL CONTAINERS CONTAINMENT.

For the disposal of spent fuel or high-level waste, the canister is required to provide absolute containment for a given period of time, e.g. during the period of significant heat emission. Therefore, during this time the container material is required to maintain its structural integrity under the expected repository conditions. Having defined the target container lifetime(s), there is then the need to select a canister material and a canister wall thickness to meet that target for the given environment.

Containers will likely fail due to mechanical instability following a period of environmental degradation (i.e. corrosion damage). Therefore, both the mechanical integrity and the (general and localised) corrosion resistance are important. Novel containers need to provide good general and localised corrosion/leaching resistance. This implies low corrosion/leaching rates and non-susceptibility to localised corrosion processes in the expected repository environment. For example, for a traditional container material such as carbon steel, the anaerobic corrosion rate in compacted bentonite is of the order of a few µm/year. In simulated groundwater solution at near-neutral pH the corrosion rate is of the order of 0.1-1.0 µm/year. In simulated cement pore water solutions the anaerobic corrosion rate of carbon steel is even lower, being of the order of 0.01–0.1 µm/year, due to the stability of a passive Fe_3O_4 film (King 2020).

The risks associated to mechanical integrity for advanced canister materials can be divided in two sub-categories, one concerned with handling, and the second concerned with disposal. While the evaluation of mechanical integrity risks can be based on specific disposal load cases, their consideration in terms of mechanical handling normally needs to be more generic.

The prediction of the durability of the containers using advanced materials (and the uncertainties associated with durability estimates), is a key input for the performance assessments.

ADVANCED MATERIALS INTERNAL STABILITY

The canister material should not adversely affect the performance of other barriers in the system. The compatibility of the selected container material with the service environment should be guaranteed both in terms of the corrosion behaviour and the mechanical loads to which the container might be exposed.

In particular, metallic materials such as carbon steel have potentially the greatest impact on the other barriers due to hydrogen gas formation during anaerobic corrosion which moves away from the canister surface by mass transport processes through both the engineered barriers of the repository and the geological barrier (Holdsworth 2014). Advanced canister materials should thus limit the production of hydrogen in the long term. Ceramics for example are characterised by very high stability in a range of aqueous environments coupled with the lack of H_2 generation.

2.2 Features, characteristics, or properties of Containers using advanced materials that contribute to achieving long-term interim storage stability and feasible implementation of geological disposal

2.2.1 Primary goals – relied upon for feasible implementation

PRACTICABILITY OF CONTAINERS USING ADVANCED MATERIALS

Advanced container materials should be preferentially chosen within a number of common, readily available materials. The choice of the material and of the production route for the canister are strongly related. Advanced materials should allow the routinely production of canisters and flaws during the production should be minimised. A particularly important aspect of the production process is related to the welding/sealing method. There must be a satisfactory method for welding or sealing applicable to a thickness in the range in question (typically several cm's). The weld depth does not need to be equal to the entire canister thickness if the requirements related to the long-term structural integrity of the weld are met. This means that the weld zone must exhibit at least the same mechanical properties as the bulk container, therefore, a smaller thickness is possible only if the mechanical properties of the sealing material are better than those of the container material. The welding method must be also suitable for remote operation, given the radiation field. The stresses in the canister wall, lid, and base, including the weld/sealing region, should not give rise to structural failure causing breach of containment for a certain period of time, e.g. during the period of significant heat emission. These stresses should be low enough to preclude the occurrence of stress-assisted failure processes (e.g., stress-corrosion cracking and hydrogen-induced cracking). The stress-reduction method (e.g. post-welding heat treatment) for a fully loaded and welded spent fuel or high-level waste canister should not damage the spent fuel or high-level waste. The guidelines used are spent fuel temperature less than 400°C (NRC 2003) and high-level waste temperature less than 500°C (COGEMA 1986, BNFL 1990).

The weld procedure should ensure any defects remaining in the canister after manufacturing are smaller than a critical crack length by a suitable margin, while the inspection process should be able to detect them. The inspection method must be suitable for remote operation, given the radiation field.

OPERATIONAL SAFETY

Shielding is an important aspect for the nuclear waste disposal canister, which is related to the reduction of worker radiation exposure during the manipulation of the container in the operational phase of the DGR. In principle, the wall thickness should be enough in order to ensure not only long-term structural stability but also that the radiation dose rate at the canister outer surface does not exceed a certain limit. Even though radiation shielding is usually not included in the design of a waste container, it is often achieved by adding an extra barrier (e.g. a concrete liner).

Advanced canister materials could offer the possibility of achieving a better radiation shielding, which could be (at least partially) integrated in the design of the waste container.

2.2.2 Secondary goal – acknowledged but not relied upon for feasible implementation

OPTIMISATION

Advanced canister materials have the potential of increasing the level of flexibility of the canister design. They can provide the ability to cope with, or to benefit from, new technical advances in waste management and materials technologies. These materials should allow for optimisation as a function of the evolution of the repository design at a reasonable cost and time.

RETRIEVABILITY.

In national programmes there may be a requirement that containers be retrievable for a period after emplacement and closure of the repository. Therefore, retrievability of novel containers needs to be considered in terms of the operational and post-closure phases of the repository. Advanced container materials must exhibit sufficient corrosion resistance for the entire period for which retrieval may be required. In addition to minimal loss of wall thickness, the material must be sufficiently resistant to embrittlement or environmentally assisted cracking so that the container can be handled without failure.

3. International examples of containers using advanced materials

This section provides a list of typical examples for the different advanced canister materials currently being studied in the international literature.

There are a number of different nuclear waste disposal canister concepts currently proposed for adoption worldwide, their configuration depending mainly on the type of waste to be disposed, the surrounding geological structure, and the material solution adopted to minimise the risk of canister integrity breakdown. Copper (i.e. Sweden and Finland) and carbon steels (i.e. Belgium, France, Switzerland, Czech Republic, Slovakia, and Hungary) are the container materials that have been traditionally considered for the disposal of SF/HLW in countries with advanced disposal programmes (Table 1). The corrosion behaviour of the types of containment systems typically envisaged in geological disposal is generally well understood, although, after many years of active research, areas of some uncertainty (typically covered by existing R&D programmes) still exist.

The feasibility of containers made from these materials has been demonstrated and the required manufacturing technology is available and mature. The container concepts also vary according to the type of waste to be stored namely spent fuel assemblies, or vitrified high level waste cylinders.

Country	Currently evaluated container materials	Buffer type, pH	Host rock	Groundwater
Belgium	Carbon steel container with cast iron insert	Portland cement, pH 13.5	Boom clay	Reducing $NaHCO_3$ waters, pH 8.5
Canada	Carbon steel member (30-47 mm) with copper coating (3 mm)	Bentonite, pH 7-8	Crystalline rock	Reducing Na-Ca-SO_4-Cl type water, saline, pH 5-8
			Sedimentary rock	Reducing Na-Ca-SO_4-Cl type water, highly saline, pH 6.3
Finland	Copper (50 mm) with massive pressure-bearing cast iron insert	Bentonite, pH 7-8	Crystalline rock	Brackish Na-Cl to saline Na-Ca-Cl waters. Eh –300 mV, pH 7.5–8
France	Carbon steel container (65 mm)	--	Callo-Oxfordian clay	Reducing Ca–Na–CO_3 waters, near-neutral pH
Japan	Carbon steel container (190 mm)	Compacted clay (pH 7-8)	Not determined	Not determined
Sweden	Copper shell (50 mm) with massive pressure-bearing cast iron insert	Bentonite, pH 7-8	Granitic rock	Dilute Na–HCO_3 waters, brackish Na–Ca–Cl waters and saline Ca–Na–Cl waters. Reducing Eh
Switzerland (Reference)	Forged carbon steel canister (140 mm)	Bentonite, pH 7-8	Opalinus clay	Reducing, near-neutral, Na–Cl waters
Switzerland (Alternative)	Carbon steel canister (120 mm) with copper coating (3 mm)	Bentonite, pH 7-8	Opalinus clay	Reducing, near-neutral, Na–Cl waters
UK (Variant 1)	Copper shell (50 mm) with massive cast iron insert	Bentonite, pH 7-8	Not determined	Assumed reducing
UK (Variant 2)	Carbon steel container (min 70 mm)	Bentonite, pH 7-8	Not determined	Assumed reducing

Table 1: Overview of the nuclear waste disposal canister concepts currently proposed for adoption worldwide Adapted from Abdelouas et al. (2022)

In the investigation of containers using advanced materials there is a strong drive towards a container solution with negligible hydrogen production during corrosion, mainly due to the uncertainties related to the impact of gas formation on the integrity of the geological barrier and the repository performance (at least for repositories in sedimentary or clay host rocks). Table 2 gives an overview on the existing experience on containers using advanced materials. A number of possibilities exist, including the use of ceramics. For these solutions, there are significant concerns related to how to maintain the mechanical integrity, the manufacture of large parts and the feasibility of the final sealing of the container. Other advanced materials are also currently taken into consideration as an alternative to bulk ceramics. These solutions include coating or cladding a carbon steel sub-structure with a highly corrosion resistant metal or ceramic (i.e. titanium, nickel, alumina) for which the long-term rate of hydrogen evolution is so low (even null for inert materials) that it remains dissolved in the pore water, and no gas phase is formed.

The development and qualification of new materials for containers still requires extensive development/studies.

Country	Novel Container	Reference
Sweden	Alumina capsule enclosed in a gas-tight metal casing	(Larker 1977) (Holdsworth 2013)
	Al_2O_3 fabricated by sintering under isostatic pressure • Sealing by diffusion bonding with TiO_2 powder • Some environmental damage evaluation	(Holdsworth 2013)
USA	Solid ceramic containers $MgAl_2O_4$ spinel (one of Yucca Mountain solutions) • Sealing by diffusion bonding with local microwave heating	(Wilfinger 1994) (Holdsworth 2013)
	Composite containers: metal structure for mechanical strength and ceramic coating/liner for chemical inertia	(Wilfinger 1994)
Germany	Focus on Al_2O_3 • Pre-stressed mechanical solution adopted for sealing • Significant environmental damage testing	(Holdsworth 2013)
France	ANDRA evaluation of Al_2O_3-SiO_2 solutions	(Baroux 2016)
Switzerland	Silicon carbide (SSiC, SiSiC, RSiC, LPSSiC, Sif/Si_3N_4) Sealing by laser beam heating with glass ceramic solders (Y_2O_3-Al_2O_3-SiO_2)	(Holdsworth 2014)
	Titanium or nickel-based alloy shell with carbon steel support	(Holdsworth 2014)

Table 2: Overview of the existing experience on containers using advanced materials.

4. Critical background information

The section highlights specific components, key information, processes, data or challenges that have a high impact or are considered most critical for implementing geological disposal, with respect to the domain of containers using advanced materials (Novel Containers).

Mechanical Integrity

The risks associated with mechanical integrity can be classified in two categories, one concerned with handling, and the second concerned with disposal.

Load cases concerned with disposal are directly related to the specific disposal system design, while load cases concerned with handling depend on the specific canister handling and emplacement method chosen for the specific disposal design.

The canister wall thickness for the chosen canister material should ensure that the stresses in the canister wall, lid, base, and weld region are less than the failure limit and this for sufficiently long time to assure radionuclide containment for the required period of time.

Environmental Damage

Advanced materials should be sufficiently resistant to environmental damage, which includes all types of corrosion to which the material is subjected due to the effect of the surrounding environment.

General corrosion/degradation

It results in a general thinning of the container wall thickness. In the case of ceramic materials the general degradation process of interest is “dissolution/leaching”. A simple method for predicting the lifetime of a container subject to general corrosion (or dissolution) is to use an empirically measured corrosion rate. The concept of using an empirical corrosion rate is typical for metals that corrode actively (also called ‘‘corrosion allowance’’ materials), for which long-term anaerobic corrosion rates are often used in the assessment of container lifetimes.

Localised corrosion/degradation

Pitting or crevice corrosion are the main local corrosion processes of concern for the integrity of nuclear waste disposal containers. For ceramic materials the localised degradation process of interest is “intergranular leaching”. Two aspects are important for the evaluation of the susceptibility of an advanced material to localised corrosion under the expected geological disposal environment:

- the initiation of the local corrosion process;
- the propagation characteristics (e.g. possibility of repassivation and self-healing).

Environmentally Assisted Cracking

Stress-corrosion cracking (SCC) and Hydrogen-induced cracking (HIC) are the main forms of environmentally assisted cracking of concern for the integrity of nuclear waste disposal containers. As for localised corrosion, it is possible to predict the long-term SCC or HIC behaviour of advanced materials based on their non-susceptibility (i.e., the absence of any cracking).

Microbially Induced Corrosion (MIC)

MIC is one of the more challenging forms of corrosion to predict over long time periods and suitable models must be developed for predicting the long-term behaviour of the container material. There are two broad approaches to assessing the threat posed by MIC:

- to determine whether the environment will support microbial activity and, if so, where and when it will occur;
- to estimate the maximum amount of damage that could occur if microbial activity in the repository is possible.

Influence of irradiation on corrosion

Gamma irradiation at the container surface and the surrounding environment may have a number of effects on the corrosion behaviour of the container:

- Radiolysis of the vapour and aqueous phases to produce oxidising and reducing radicals and molecular products;
- Interaction with semiconducting passive oxide films;
- Reduction in the number of viable microbes at, or near, the waste package surface resulting in a potential retardation of MIC.

Impact on engineered and natural barriers

The canister material should not adversely affect the performance of other engineered barriers or perturb the host rock characteristics. Hydrogen gas generation due to the anaerobic corrosion of advanced candidate materials is thus a focal point. Hydrogen gases may migrate through the engineered barrier system and the natural geological barrier. However, excessive hydrogen gas production could cause high pressures in the system, which would result in the formation of fractures at the level of both the engineered barriers and the host rock or accelerate the migration of volatile or dissolved radionuclides through the repository structures. Hydrogen formation does not represent a problem when the gas formation is less than the gas transport limit of the host rock. In that case the gas production rate is sufficiently low for the hydrogen to simply dissolve in the pore water or escape from the repository via two-phase flow.

Fabrication

While the mechanical and very-long-time corrosion properties of candidate materials are key selection criteria, verifying the feasibility and effectiveness of canister closure and inspection solutions in a hot cell environment is equally important. The remote handling and final sealing of spent fuel rod containment canisters is challenging. In order to guarantee the chemical properties of the nuclear glass and spent nuclear fuel, their temperature should not to exceed ~400-450°C (Holdsworth 2014). This threshold temperature induces directly a constraint on the energy allowed at the surface of the container material during the welding/sealing or stress relief operations, and more precisely on the applied temperature and the heating duration.

Costs

Costs can be categorised under two sub-categories:

- Research and development costs, required to get the canister waste disposal concept to the point where it provides a feasible solution and could be implemented in a safe, reliable and acceptable way;
- Production unit costs, related to the final cost of a candidate canister solution. These are sensitive to raw material costs, market fluctuations, required product form and quantity.

For advanced container materials the research and development costs can be very large due to the need to investigate all the above mentioned aspects.

4.1 Integrated information, data or knowledge (from other domains) that impacts understanding of containers using advanced materials (Novel Containers)

- Identify an appropriate buffer, and confirm its properties, behaviour and evolution for the selected repository concept (See DI 3.3.1 Buffers). The corrosion/degradation of advanced container materials depend not only on the properties of the container material but also on the corrosivity of the environment to which it is exposed, which evolves with time. One important role of the buffer is to protect the container from mechanical damage and corrosion. The environmental parameters that can potentially influence the corrosion/degradation behaviour of advanced container materials are: temperature, pH of the buffer material, degree of water saturation of the buffer, chemical composition of the pore water solution (including the presence of aggressive species) and radiation levels.

- Understanding of the disposal environment (See DI 3.4.1 EBS system). The corrosion behaviour of advanced container materials (mechanisms, corrosion/dissolution rates, gas generation rate) will vary depending on the post-closure environmental conditions. The expected geochemical evolution of the EBS will be affected by several factors, most notably temperature, reactions between EBS materials, and the chemistry of groundwaters penetrating the EBS from the host rock.

- Understanding the hydrogeological and hydrogeochemical environment (See chapter 4.11 Site descriptive model). The surrounding host rock at planned repository sites sets limitations for canister materials. Canister failure can be driven by for example groundwater, microorganisms or mechanical factors linked to the host rock. In addition, temperature allowance of canisters differs between the host rock types. In addition to this, the geochemistry of the buffer surrounding the container will gradually be modified as the water coming from the host rock penetrates the EBS. As a consequence, the environment surrounding the containers will change from unsaturated to saturated conditions. Aggressive species eventually reaching the container material surface will also depend on the chemical conditions of the host rock. Understanding the hydrogeological and hydrogeochemical environment is thus an important issue which will impact how the EBS (and thus the chemical environment at the container material surface) will evolve.

5. Maturity of knowledge and technology

This section provides an indication of the relative maturity of information, data and knowledge for disposal of containers using advanced materials (Novel Containers). It includes the latest developments for the most promising advances, including innovations at lower levels of technical maturity where ongoing RD&D and industrialization activities continue.

5.1 Advancement of safety case

Consideration of candidate material solutions for the containment of nuclear waste has been the topic of research during the past 40-50 years. However, the study of advanced container materials is not mature at this point. For example, the use of ceramics for nuclear waste disposal containers was first seriously considered in the 1970s (Mattson, 1980; Bienek, 1984) and has continued to be an option (Holdsworth, 2013; Baroux, 2016; Adams, 2000; Wötting, 2007; Kerber, 2013) albeit apparently without a high level of commitment since the early 2000s. There seems to be insufficient motivation to invest in the research which would be necessary to overcome known difficulties when feasible metallic solutions have already been recognised (Holdsworth, 2013). The authors are not aware of any safety case based on advanced canister materials to date.

5.2 Optimisation challenges and innovations

The development and qualification of advanced materials for containers still requires extensive development/studies. The diversity of the solutions envisaged leads to a great variability of the tests to be carried out (mechanical for ceramics, quality of the coating for anti-corrosion coating solutions, etc.).

5.3 Past and ongoing (RD&D) projects

Past (RD&D) Projects:

- *SCELLMO (Andra) –2014-2015 : Scellement par traitement thermique assisté par micro-ondes, de surconteneurs en matériau céramique – Etude des propriétés physico-chimiques.*
- *NOUMEHA (Andra)- 2017-2018 : Nouveaux Matériaux pour l'alvéole HA*

These projects did the proof of concept for the sealing of ceramics using microwaves. Using alumina-based ceramics, different sealing materials (glasses) were tested and they were compared in terms of material coupling with microwaves, lixiviation behaviour, mechanical properties of the assembly. In NOUMEHA, modelling of a prototype microwave oven were also achieved in order to study the thermal during the sealing of a canister. The results showed that materials as well as heating cycles need to be optimised.

Ongoing (RD&D) Projects:

- *EURAD Work Package ConCorD - Container Corrosion under Disposal conditions*
- *COCONUT project (Andra) - Composite container for long-term nuclear waste disposal.* This project proposes a new concept of container for storage of high-level radioactive waste (HLW) which consists in making a corrosion-protective external shell using a cold spray coating of blend copper-silicon carbide on the steel internal shell thus constituting a dual shell container. It is expected that proposed material system will match the requirements for HLW container and guarantee high corrosion resistance during whole period of waste storage.

6. Uncertainties

- Long-term properties

Humanity has only a few decades of experience with most of the advanced materials considered for disposal canisters. As a result, there are important uncertainties related to their long-term properties. Such properties that are relevant to canister performance are environmental degradation mechanisms and rates, and chemical-mechanical interactions such as the degradation of mechanical properties due to interactions with the environment. These uncertainties and the lack of archaeological or natural analogues contribute to a reduced robustness of canister lifetime predictions compared to traditional materials.

- Manufacturing ability and sealing/welding feasibility and quality

For some advanced materials (e.g. bulk ceramics) there is currently no ability to manufacture a canister at necessary scale. Furthermore, the feasibility and quality of the final seal/weld is uncertain or currently impossible. Solving such issues would require several decades and a significant investment in research.

- Costs

Several advanced materials (e.g. nickel, titanium, SiC coatings) are expensive. Even if their high corrosion resistance or other properties allow only a small amount of material to be used (e.g. if employed as coatings) the prediction of the evolution of costs over decades until implementation has significant uncertainties.

7. Further reading, external Links and references

7.1 Further Reading

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