Radioactive Waste Management
NEA/RWM/IGSC(2015)1/REV1
March 2015
www.oecd-nea.org

Relevance of Gases in the Post-closure Safety Case for Radioactive Waste Management

A Position Paper from the Integration Group for the Safety Case (IGSC)

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

Unclassified **NEA/RWM/IGSC(2015)1/REV1**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **11-Mar-2015**

English - Or. English

NUCLEAR ENERGY AGENCY
RADIOACTIVE WASTE MANAGEMENT COMMITTEE

NEA/RWM/IGSC(2015)1/REV1
Unclassified

Integration Group for the Safety Case (IGSC)

RELEVANCE OF GASES IN THE POST-CLOSURE SAFETY CASE

An IGSC Position Paper

December 2014

1) Update of classification from" Official Use" to "Unclassified".
2) Minor change on page 3.

For any further information, please contact Gloria KWONG (gloria.kwong@oecd.org)

JT03372119

Complete document available on OLIS in its original format

English - Or. English

RELEVANCE OF GASES IN THE POST-CLOSURE SAFETY CASE

AN IGSC POSITION PAPER[1]

1. Introduction

In the postclosure phase of a deep geological repository for radioactive waste, significant quantities of gases may be generated from various sources. The most important gas generating process is anaerobic metal corrosion. Additionally, degradation of organic matter by bacterial activity [mainly important for intermediate level waste and low-level waste (ILW and LLW) repositories] and water radiolysis contribute to gas formation. Non-radioactive gases can be important because of potential pressure related impacts on the engineered barrier system and geological host formation, and their role as a carrier gas for transporting radioactive gases. Repository designer may thus face a possible conflict of goals: while the design strategy of a disposal system is to provide isolation and containment, the non-radioactive gases may need to be dissipated to minimize any adverse effects from pressure build-up in the repository system.

Besides the large amount of non-radioactive gases, small amounts of radioactive gases are also generated and can have direct radiological consequences. Due to a usually large initial inventory and a longer half-life, ^{14}C if present in (or converted to) gas form can be of safety relevance depending on its degree and rate of conversion to methane and the period of confinement in the geological repository before it reaches the biosphere. Depending on the waste type, the concept and scenario, in some studies a fraction of volatile ^{129}I might be considered to be released from the waste. Radon presents a specific case as it will be continuously formed by radioactive decay of its parent nuclides during the containment period but also afterwards, when parent nuclides migrate throughout the barrier system. When applicable, ^{222}Rn is also particularly studied in the framework of operational period. Noble gases and tritium are not an issue for the post-closure safety due their short half-lives but may be considered for the operational period.

Gas production might also influence geochemical conditions in the near field and/or the host formation in different ways. A potential positive effect is a lower dissolution rate of spent fuel due to the reducing conditions imposed by the generation of hydrogen gas, while a potential negative effect could be a higher solubility of actinides due to the lower pH conditions imposed by the presence of gaseous CO_2. Consequently a sound safety strategy addressing these issues and a body of robust arguments are needed to support a post-closure safety case in order to give an adequate level of confidence that gas generation is not an issue likely to compromise the safety of a deep geological disposal system.

Gas generation and transport in deep geological repository have been studied for more than 15 years in a series of successive international projects. These include the PEGASUS (Heimbach *et al.*, 1996), EVEGAS (Manai, 1997), PROGRESS (Rodwell, 2000) and the GASNET (Rodwell *et al.*, 2003) projects. A comprehensive review of several studies was also issued on this subject (Rodwell *et al.*, 1999). While R&D on gas issues continued from the early 2000s within the national programmes, there was a hiatus of several years for comprehensive multinational projects. In 2009, the FORGE (Fate Of Repository Gases)

---

[1] Key Authors: M. Capouet[1]; U. Noseck[2]; M. Navarro[2]; A. Rübel[2]; A. Van Luik[3] and X. Sillen[1]
[1]ONDRAF/NIRAS (Belgium); [2]GRS (Germany); [3]DOE-WIPP (USA)

project, under the auspices of the European Commission, was launched with participants from radioactive waste management organisations, regulators and academia. In this context, the IGSC revisited the topic

from a strategic point of view, and issued this position paper to support the IGSC viewpoint, based on the results of the FORGE project (Shaw, 2013) and safety cases developed in various national programmes.

2. Gas sources in a deep geological repository

Gas generating processes in a repository include anaerobic metal corrosion, (bio-) chemical degradation of organics, and radiolysis of water and waste, from which gaseous radionuclides may also be released.

Corrosion processes of metal in geological repositories have been extensively investigated in many national programmes, with the objective to demonstrate that the containment requirement of radionuclides within the multiple engineered barriers can be met. R&D performed in the pursuit of that objective has also benefited to the evolution of the corrosion gas source term as advances in mechanistic understanding of the underlying processes have been achieved. Long-term corrosion experiments of steel exposed in conditions simulating a disposal system show carbon steel corrosion rates ranging from a few to tens of nanometres per year in cement-based systems, to tens of microns per year in bentonite-based systems (Nagra, 2008; Serco, 2010; Newman *et al*., 2013). An asymptotic decrease of carbon steel corrosion rates has been observed in experiments and can be explained by the progressive passivation of steel where a protective corrosion product layer is formed on the canister surface. In the case of a copper canister, container lifetimes are very long and gas generation rates are extremely low due to the thermodynamic stability of copper (King *et al*., 2010).

Once confidence is established that metallic barriers can provide containment as required by the national regulations under stable conditions, R&D programmes tend to shift towards the study of corrosion processes under environmental conditions that will prevail during transients which immediately follow closure of the repository such as the resaturation and/or the thermal phase. For heat-emitting wastes such as spent fuel, the thermal transient can extend over several centuries. Unsaturated conditions might also prevail for a significant period of time, depending on the type of host rock and the repository design. In some clay-based concepts, parts of the near field may remain only partially saturated for decades. Steel corrosion in an unsaturated, high humidity environment is not fully understood and few corrosion data are available. However, recent results for steel corrosion in cementitious material at 100% humidity show corrosion rates similar to those observed in liquid water (Newman *et al*., 2013). The effect of perturbations of the system after closure, such as the ingress of aggressive species, has also been investigated in several programmes (Kursten *et al*., 2004)

In some cases, availability of water might be a limiting factor for gas generation. This might apply in particular to repositories in dry host formations, like rock salt, for which unsaturated conditions are also expected to prevail for a significant time period after final closure (Beuth *et al*., 2012).

A variety of gases can be produced from radiolysis, hydrolysis and microbial degradation of cellulose, resins, bitumen and plastics present in low-level and intermediate-level, long-lived wastes (LLW and ILLW) (Rodwell *et al*., 2003). Rates of gas generation from LLW under repository conditions have been quantified in large scale experiments (Rodwell, 2000; Molnar *et al.* in Shaw, 2013). A biogeochemical reaction-transport model of one such experiment has shown an estimate of gas production rate reasonably consistent with the test data (Small *et al*., 2008). Nevertheless, the diversity of LLW and ILLW, the waste package heterogeneities, the evolving conditions of deep geological repositories and their possible local variability and microbial diversity in the environment are factors that would limit accurate predictions of the long-term gas generation rates in a repository.

Laboratory experiments have shown the remarkable adaptation behaviour and versatility of microbes in environments anticipated in a geological repository. Their possible impacts range from concrete carbonation through the production of CO_2 to the formation of volatile radioactive compounds via the methylation of iodine and selenium (Francis in Shaw, 2013). Beyond the waste package, an adequately backfilled and sealed geological repository normally constitutes a harsh environment for microbes to be active, due to the lack of free space, slow diffusive transport of metabolites and often a lack of suitable carbon sources, electron donors or acceptors. Such environments are expected to severely limit, if not rule out, microbial activity, although supporting data are limited. It has been noted, however, that microbial activity can in some case be beneficial, e.g. certain microbes are capable of using hydrogen as a source of energy and therewith acting as a sink for hydrogen. Projecting longer term microbe behaviour for a specific repository setting encounters issues of variability and the long-term viability of microbes as the near-field environment stabilises.

3. Gas transport in deep geological repositories

Gas transport mechanisms are highly dependent on the type of host rock and the design and materials of the EBS (e.g. the type of backfill and sealing materials used).

In a disposal system saturated with groundwater (or close to saturation), dissolved gas can be transported via diffusion in pore water. No particular issues are expected for systems in which the gas generation rate is low enough for all gas to be continuously evacuated through this well-characterised process. Complexity – and differences between disposal systems – arise if the capacity for diffusive removal of dissolved gas is exceeded and a discrete gas phase is formed: characterisation of advective gas flow through natural or engineered low-permeability porous materials is a challenging endeavour, especially when those materials are close to saturation with water. For more than two decades, efforts to characterise gas transport modes have been pursued in laboratory and in situ tests while process models have been developed in parallel.

In the laboratory, the identification and characterisation of advective gas transport modes in small samples of natural or engineered low-permeability material is complicated by a high sensitivity of the results to the experimental conditions and the initial state of the samples (Rodwell *et al*., 1999 and 2003; Shaw, 2013). Some of these conditions can be constrained by adequate control of the initial saturation, the stress or strain boundary conditions and the geometry of the experimental setup. Nevertheless, for natural materials, sample variability and interfaces with the experimental setup may still lead to very different results for otherwise similar tests: gas always takes advantage of heterogeneities to flow through the path of least resistance. For cementitious materials, large variability in gas migration properties might also show up as a result of sensitivities to manufacturing factors such as curing conditions and formulations (Rodwell *et al*., 1999). An additional complexity presented by cement-based systems is the dynamic physico-chemical evolution of the materials. This evolution can have different effects on porosity and gas permeability as these can be affected, for instance, by crack formation but also pore clogging due to formation of new phases.

In situ characterisation of gas transport in the host rock around underground laboratories presents additional challenges such as the presence of a disturbed zone around the experimental setup. Modelling studies reveal that the outcomes of such experiments are strongly dependent on the extent and the properties of this disturbed zone (Levasseur *et al*., Gerard *et al*., Granet and de La Vaissiére in Shaw, 2013). A correct interpretation of *in situ* test results would thus ideally require an adequate characterisation of this zone. In absence of this, gas behaviour might be deduced from the injected gas volumes and observed pressures albeit with a considerable amount of uncertainties. After-test forensic analyses may also support the parameter identification process provided that the perturbations induced by gas transport can be distinguished from these resulting from the installation of the experimental setup.

3.1 Gas transport in clay systems

A large amount of laboratory experiments have been performed at the end of the last century to characterise the transport of gas under defined pressures through bentonite and other clay barriers (among others by Horseman *et al*., 1996; Horseman *et al*., 1999; Harrington and Horseman, 1999). These have been complemented by in-situ experiments and additional laboratory tests such as those reported in Rodwell *et al*. (2003). At the time, a consensus emerged among experimentalists that due to high gas entry pressures, the transport of gas through compacted clays saturated with water or close to saturation is only possible by the creation of specific gas pathways, *i.e.* a network of fissures or fractures. As a consequence, dilatant behaviour and the creation or reactivation of discontinuities in the material should be expected.

During the more recent FORGE project, additional laboratory and in-situ experiments on gas transport in clay systems (e.g. Birgersson and Karnland, Cuss *et al*., Harrington *et al*., Zhang *et al*., Graham *et al*., in Shaw, 2013) have confirmed these earlier conclusions – dilation has been clearly evidenced in laboratory experiments on clays. Interestingly, the evaluation of water mass balances indicate no significant loss of water even after many hundreds of days of gas testing at elevated pressures, which strongly hints at separate gas- and water-filled networks.

Experimental evidence from in situ testing and laboratory tests performed on artificially damaged samples (Zhang *et al*., Svoboda and Smutek in Shaw, 2013) confirm that around a repository, discontinuities in the disturbed zone can act as preferential gas transport pathways when a threshold gas pressure is reached, and these pathways may shut down once the pressure drops. Besides the disturbed zone, the possibility of localised gas transport along interfaces between repository components has also been identified (Popp *et al*. in Shaw, 2013).

In laboratory tests, hydraulic conductivity measurements performed before and after gas flow generally do not exhibit notable differences. *In situ*, ample evidence has been collected of spontaneous sealing of discontinuities in confined, water saturated clay systems (SELFRAC, 2007; Tsang *et al*., 2011; Li, 2013). *A priori*, discontinuities activated by gas transport should thus not act afterwards as preferential groundwater and solute transport pathways. This has been confirmed to be the case in the short term by in-situ experiments such as RESEAL (RESEAL, 2009). Given that gas release may spread over quite long periods, it should be checked, however, that other perturbations (e.g. alkaline plume) will not in the meantime negatively affect this “self-sealing” capacity.

Two-phase flow is a possible transport mode in materials with a lower gas entry pressure, such as sand-bentonite mixtures and possibly in some natural clayey formations at a large scale due to heterogeneities such as sandy facies. In these cases, it can be possible for a pressurised gas phase to displace porewater, without the creation of new, gas-specific pathways. Note that non-disruptive gas flow is also possible for materials with high gas entry pressures provided that the degree of saturation with water is low enough for continuous, water-free pathways to be maintained.

3.2 Gas transport in crystalline rock systems

For granite formations, the major concern with respect to gases is related to the integrity of the bentonite buffer, commonly used to protect waste containers in such formations. The gas transport processes in the buffer are those mentioned for a repository in clay but relevant parameter values like gas entry threshold might be different due to differences in structure and mineralogical composition. In a highly compacted bentonite buffer the gas entry pressure is high enough to prevent initiation of two-phase flow and dilation pathways are the main gas transport mechanism. In contrast to relatively tight clay formations, build-up of high gas pressures in granite formations is unlikely, since existing fractures already provide migration pathways for generated gases (SKB, 2011). Therefore, a harmful effect of gases on the integrity of the granite host rock is not an issue. Further, the concepts followed in Sweden and Finland are based on copper canisters, where gas generation rates by corrosion are extremely low and without any negative consequences for the buffer. The iron insert of the copper canister may generate high amounts of gas by corrosion if the copper shell is damaged. Due to the high stability of copper it is expected that most of the canisters will stay intact within their typical design lifetime of 1 million years. The canister fabrication and sealing processes are expected to produce canister that are tight at deposition (SKB, 2011). Defective canisters are not assumed to occur before 100 000 years after repository closure. In a scenario where a canister is damaged e.g. by an earthquake, but the buffer is intact, the buffer is expected to retain its properties throughout the gas-transport period so that gas-induced pathways are likely to close and seal when gas production ceases. Also for hypothetical scenarios with an assumed number of canisters with a pinhole defect, the impact of gas formation is expected to be limited and local (SKB, 2011). A pinhole is still a barrier in terms of allowing the movement of reactants and corrosion products, but typically very conservative assumptions are made in evaluating hypothetical initial defect scenarios.

3.3 Gas transport in salt systems

Due to the unsaturated conditions prevailing over very long times in the expected evolution of dedicated salt repositories, the process of gas dissolution does not play a major role. Gas transport is therefore dominated by advection in the gas phase. In case of low liquid saturation, gas can flow without needing to displace the liquid phase.

Rock convergence and subsequent compaction of crushed salt backfill are important processes in salt concepts. If backfill porosity is reduced to a few percent, saturation increases and the vapour-liquid equilibrium may be shifted towards further gas dissolution. Rock convergence, gas and liquid flow are coupled processes: On the one hand convergence will increase the pore pressure and therewith initiate gas flow. On the other hand, the flow of gas will modify the pore pressure, and thus act on the compaction rate. This interplay can lead to a complex flow pattern inside a repository built in rock salt. Since convergence and compaction of crushed salt strongly depends on temperature, there is an initial gas flow from faster converging hot to slower converging cold areas. This implies that gas is accumulated in cold areas in which elevated pressures will evolve as soon as convergence progresses here, too. These effects have been observed in modelling studies for a hypothetical repository at the German Gorleben site (Larue *et al*., 2013). Further, gas pressures might also act as a dynamic barrier by preventing liquids from entering the repository. However, many properties of highly compacted crushed salt backfill which are needed to quantify gas transport are still not well known.

The salt host rock itself is impermeable for gas at pressures well below the minimum principal stress. Gas flow will therefore follow preferential flow paths given by the engineered barrier system (EBS), the excavation disturbed zones (EDZ), and material interfaces. Gas will cause macroscopic fractures in the host rock if gas pressure reaches the minimum principal stress of the rock. Due to stress heterogeneities at the microscopic scale gas will already infiltrate at slightly lower pressures on grain boundaries without compromising the host rock’s integrity. It is important to mention that site-specific aspects may also play a crucial role. Indeed, a more heterogeneous formation such as the bedded Salado formation at the Waste Isolation Pilot Plant repository in New Mexico, USA, would allow gas to escape away from the repository along nearly horizontal higher permeability, but typically saturated, interlayers (Nemer, 2010).

4.1 Clay- and crystalline rock systems

Similar approaches are used for process-level modelling of gas transport through low permeability porous media such as EBS materials (bentonite in a crystalline rock) or the host rock itself (for a repository in clay). Conventional two-phase flow models are generally used to represent non-disruptive gas transport in porous media when the gas entry pressure is much lower than confinement stresses. If the gas pressure exceeds the minimum confinement stress, transport of gas occurs via the propagation of tensile fractures. The modelling of this transport mode is complex because initiation and propagation of discontinuities are intrinsically linked to the small scale local stress distributions, affected by the presence of heterogeneities. Several conceptual approaches have been proposed to represent disruptive gas transport (Rodwell *et al*., 1999; Shaw, 2013), one of these being two-phase flow models extended with semi-empirical hydro-mechanical couplings i.e. stress and/or damage-dependent transport properties.

Although these models may reproduce experimental observations to some extent, they rely on case by case tuning of the coupling parameters. To date, the large degree of freedom left to the modeller in the choice of parameters that cannot be directly measured (or which could only be obtained by destructive techniques) limits the predictive capability of such models. Models able to capture discontinuity creation and propagation caused by disruptive gas transport might remain out of reach because of the inherent limitations associated with the characterisation of natural porous media.

4.2 Salt systems

For salt repository concepts, the expected evolution is marked by very dry conditions. However, for less likely evolutions the possibility of brine intrusion has to be considered. Modelling fluid transport on the repository scale is a demanding task especially because of the interactions between flow and rock convergence mentioned before. In the nineties of the last century, these processes have been simulated by models that use networks of one- or zero-dimensional structures with sophisticated physical behaviour (Hirsekorn *et al*., 1999; Martens *et al*., 2002). Such models are able to capture repository scale interactions with an affordable amount of calculation time but they usually do not fully incorporate the classical two-phase flow theory. Other approaches use standard two-phase flow codes that have been extended by processes that are typical to salt repositories (Larue *et al*., 2013). Such models require a significant amount of calculation time and can be regarded as complementary to the before mentioned more efficient simplified model types.

Gas pressure as well as gas transport velocity strongly depend on porosity and liquid saturation. Even if the water content of crushed salt is very low, saturation will become relevant if the backfill porosity reaches the range between 0 % and 2 % in the long term. Also, pore structure and water mobility are not well known for low porosities so that the applicability of two-phase flow models for low backfill porosity conditions is still an open question. These aspects show that there is a general quantification problem in modelling gas transport in crushed salt used as a long-term sealing material in a converging host rock. This uncertainty has to be addressed in the safety assessment or the repository concept has to be changed.

The pore space of the backfill is not the only flow path for gas. Gas may also flow through excavation disturbed zones, along material interfaces and in some cases along the grain boundaries of undisturbed rock salt. All these pathways require different treatment according to their characteristic properties. Some aspects may be sufficiently covered by the classical two-phase flow theory. Others clearly call for enhanced modelling approaches. Classical two-phase flow models are less well suited if gas flow follows localised channels. Localised flow will occur along fractures and fissures of the excavation disturbed zone or along the interfaces connecting the seals with the host rock. Gas flows also tend to localise if preferential flow paths are opened by high pressures (“pathway dilation”).

The permeability of sealing materials like salt concrete or of discontinuities may depend on fluid pressure and the local stress state. In this case, hydro-mechanical models or two-phase flow models introducing a pressure dependency of permeability or permeability change are more appropriate.

5. Radiological impact

Gas can potentially affect the radiological consequences resulting from a deep geological repository in two ways. The first one corresponds to the direct release of radioactive gas itself. The second is of an indirect nature: if large amounts of inactive gas are produced in the repository, these might enhance radionuclide transport of dissolved radionuclides within the disposal system by displacing contaminated water, acting as carrier gas for volatile nuclides or inducing damage to the multi-barrier system as a result of excessive pressures.

Due to a potential large initial inventory and a longer half-life, gaseous ^{14}C can be of safety relevance depending on the period of confinement and transport of this gas in the geological system before it reaches the biosphere. The behaviour (e.g. solubility, transport) and impact (e.g. accumulation in the biosphere) of gaseous ^{14}C strongly depends on its speciation. The behavior of ^{14}C is a matter of further research and will be addressed in the CAST project as part of the EC Seventh Framework Programme. Depending on the waste and the design, scenarios in which a fraction of volatile iodine can be released from the waste might also be considered. However, the contribution of radioactive gas to the total dose rate in the biosphere after closure is usually considered minor, except for dry systems in which radioactive gas releases can make up most of the radiological impact (e.g. Larue *et al*., 2013).

The influence of non-radioactive gas on radionuclide transport mainly depends on the balance between non-radioactive gas production rate and gas transport. If the gas production rate is low enough for the gas to be dissipated by dissolution in groundwater and diffusion, then the radionuclide transport in the liquid phase is not affected. If conditions in the repository are such that two-phase flow can develop, gas might displace contaminated pore water. In case of gas transport by pathway dilatancy, experimental evidence suggests that only little water is moving with gas in clay materials (Jacops *et al*. in Shaw, 2013). Nevertheless, radioactive gas mixed with inactive gas will be transported during breakthrough events. After gas breakthrough, the well-documented self-sealing properties of a bentonite-based barrier and/or clay host rock should prevent the persistence of preferential pathways.

6. Treatment in safety assessment & management of uncertainties

The dominant gas generation process for geological disposal of vitrified high-level waste and spent fuel is anaerobic corrosion of steel. In performance assessment, the rate of gas generation by metal corrosion is generally determined as the product of the surface area and the corrosion rate. A large body of knowledge about metal corrosion rates in saturated systems is available (Smailos *et al*., 1999; King, 2008; Shaw, 2013). Residual uncertainties on the actual conditions prevailing in the repository and their evolution in the long term shall be addressed in the safety assessment. Depending on the design, on the nature of the metal, and the host-rock the long term corrosion rate of the metallic containers of HLW in saturated and non-disturbed disposal systems might be low enough so that all the generated gas can be fully evacuated by dissolution and diffusion alone. For LLW and some ILW, accessible surface area of the metal are often conservatively estimated since they cannot be accurately determined, especially for older pre-packaged wastes. Gas-generation and transport modelling results based on such estimates will likely overstate the potential importance of the gas generation and transport processes.

Gas generation in unsaturated systems, such as in salt formations, may be limited by the availability of water.

Diffusive transport of dissolved gas through groundwater is a well understood and easily modelled mechanism. Models are also available to represent two-phase flow when it applies. For low permeability clayey material and for very low porosity and low permeability materials like compacted salt grit, there are conceptual limitations to developing a hydro-mechanical model able to capture gas flow through dilatant pathways. Extension of two-phase flow models coupled to mechanical poro-elasto-plastic/damage models calibrated with available *in situ* measurements might circumvent these limitations to some extent, and provide a tool for use in a safety assessment provided that simplifying assumptions and their conservatism are documented and remembered in interpreting results.

In addition to the epistemic uncertainties that may be reduced by more characterisation efforts, gas transport through discrete features suffers also ontic – irreducible – uncertainties due to the complexity of some of the processes and features involved, such as damage propagation and pathways instability. In order to account for this inherent limitation, different strategies exist. With respect to the source term, uncertainties can be reduced by the estimation of more realistic corrosion rates, dissolution rates, and specific surfaces. A second option is to optimise the design of the repository, by (i) minimising the amount of gas producing materials, and/or (ii) minimising gas generation rates by optimisation of geochemical conditions and/or (iii) limiting the availability of water within the engineered barrier system.

Comparable strategies can be followed with respect to gas transport. A reduction of the uncertainty associated with complex gas transport modes might be sought through the choice of EBS materials through which gas transport can be more easily characterised. The design for gas transport might be optimised by maximising the exchange surface for transport of dissolved gas, *i.e.* adapting the repository geometry and/or organising storage & transport capacities to cope with gas production rates, e.g. by the choice of porous, non-compacting backfilling material, or by explicitly providing long-term stable gas evacuation pathways, e.g. Engineered Gas Transport System (EGTS) (Nagra, 2008b).

7. Importance for the safety case

Repositories are designed to contain radioactive materials for as long as is possible. Gas generation and the physical processes it may induce ought not determine repository safety, but may be a contributing factor. Even if it is not a primary determinant of safety, it may still be a source of an unwelcome degree of uncertainty.

The foregoing discussion has described, based on decades of previous work, the state of the art in considering gas generation, evolution and transport in the context of deep geological repository system performance. Uncertainties in modelling gas-related processes have been discussed, as have strategies for dealing with uncertainties through doing more scientific work, redesigning the repository, or operationally controlling the content of the repository.

Determining whether or not such additional scientific, design or operational control activities need to be undertaken is aided by sensitivity analyses. If overall repository safety is not strongly dependent on processes related to gas generation and transport, then existing information may allow a case for repository safety to be credibly made based on conservative modelling of gas generation and transport processes. Long-term gas-process related effects on repository performance must be evaluated in the context of applicable safety requirements. In instances where requirements are likely to be met, a conservative gas generation and transport approach in the context of a comprehensive safety case can convince the implementer, key stakeholders and regulators to allow the project to move forward in its evolution.

If gas-generation and transport processes are relatively important to determining long-term repository safety, then there are options to be considered to reduce uncertainty and thereby allow more realistic safety evaluations to be done, or redesigning the proposed repository system. Beyond the implementer's conviction, the confidence in uncertainties management in the safety case should be shared by regulator and others stakeholders. A strategy for obtaining a broader base of support for a construction license may include scientific or design work to reduce uncertainties in order to meet their expectation.

References

Beuth, Th., Bracke, G., Buhmann, D., Dresbach, Ch., Keller, S., Krone, J., Lommerzheim, A., Mönig, J., Mrugalla, S., Rübel, A. and Wolf, J.: Szenarienentwicklung: Methodik und Anwendung. Bericht zum Arbeitspaket 8. Vorläufige Sicherheitsanalyse für den Standort Gorleben. GRS-284, 2012.

Harrington, J.F., and Horseman, S.T.: Gas Transport Properties of Clays and Mudrocks, Geological Society, London, Special Publications 158 (1): 107–24. doi:10.1144/GSL.SP.1999.158.01.09, 1999.

Hirsekorn, R.-P., Boese, B. and Buhmann, D.: LOPOS: Programm zur Berechnung der Schadstofffreisetzung aus netzwerkartigen Grubengebäuden. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-157, Braunschweig, 1999.

Heimbach, H., Steinmetz H.J. and Odoj R.: Gas Generation in Supercompacted Products, Proceedings of the PEGASUS Progress Meeting on Gas Generation and Release in Radioactive Waste Repositories, Rapolano Terme, Italy, 14-16 June 1995, European Commission Report EUR 16746 EN, 1996.

Horseman, S.T., Higgo, J.J.W., Alexander, J. and Harrington J. F.: Water, gas and solute movement through argillaceous media, Nuclear Energy Agency Rep. CC-96/1, OECD, Paris, 1996.

Horseman, S.T., Harrington, J.F. and Sellin. P.: Gas Migration in Clay Barriers, Engineering Geology 54 (1–2): 139–49. doi:10.1016/S0013-7952(99)00069-1, 1999.

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

King, F., Lilja, C., Pedersen, K., Pitkänen, P. and Vähänen, M.: An update of the state-of-the-art report on the corrosion of copper under expected conditions in a deep geologic repository. SKB TR-10-67, Svensk Kärnbränslehantering AB, 2010.

Kursten, B., Smailos, E., Azkarate, I., Werme, L., Smart N.R. and Santarini G., COBECOMA, State-of-the-art document on the Corrosion Behavious of Container Materials, Final report, European Commission Report, 2004.

Larue, J., Baltes, B., Fischer, H., Frieling, G., Kock, I., Navarro, M. and Seher, H.: Radiologische Konsequenzenanalyse. Bericht zum Arbeitspaket 10. Vorläufige Sicherheitsanalyse für den Standort Gorleben. GRS-289, Gesellschaft für Anlagen- und Reaktorsicherheit, Köln, 2013.

Li, X.-L.: “TIMODAZ: A successful international cooperation project to investigate the thermal impact on the EDZ around a radioactive waste disposal in clay host rocks.” Journal of Rock Mechanics and Geotechnical Engineering 5, no. 3, 231-242, 2013.

Martens, K.-H., Fischer, H. and Romstedt, P.: Beschreibung des Rechenprogrammes MARNIE. 135 Seiten, GRS-A-3027, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH: Köln, 2002.

Nagra: Effects of post-disposal gas generation in a repository for low- and intermediate-level waste sited in the Opalinus Clay of Northern Switzerland. Nagra Technical Report, NTB 08-07, Wettingen, Switzerland, 2008.

Nagra: Corrosion of carbon steel under anaerobic conditions in a repository for SF and HLW in Opalinus Clay, Technical report 08-12, 2008b.

Manai, T.: Evegas, European validation exercise of gas migration models through geological media (Phase 3 – final report), European Commission Report EUR 17557EN, 1997.

Nemer, M.B.: Analysis Package for Salado Flow Modeling: CRA-2009 Performance Assessment Baseline Calculation, Sandia National Laboratories, Carlsbad, NM., ERMS 552956, 2010.

Newman, R.C., Wang, S., Johnson, L. and Diomidis, N.: Carbon Steel Corrosion and Hydrogen Gas Generation in Cementitious Grout under Anoxic Conditions, in proceedings of the 5th International Workshop on Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems, October 6 – 10, Asahikawa, Japan, 2013.

RESEAL, RESEAL II, a large-scale *in situ* demonstration test for repository sealing in an argillaceous host rock – Phase II", final report, European Commission Report EUR 24161 EN, 2009.

Rodwell, W.R., Harris, A.W., Horseman, S.T., Lalieux, P., Müller, W., Ortiz Amaya L. and Pruess K.: Gas Migration and Two-phase Flow through Engineered and Geological Barriers for a Deep Repository for Radioactive Waste; a joint EC/NEA status report, European Commission Report EUR 19122 EN, 1999.

Rodwell, W.R. (Ed.): Research into gas generation and migration in radioactive waste repository systems (PROGRESS project). European Commission Report EUR 19133 EN, 2000.

Rodwell, W.R., Norris, S., Mäntynen, M. and Vieno, T.: A thematic network on gas issues in safety assessment of deep repositories for radioactive waste (GASNET). European Commission Report EUR 20620 EN, 2003.

Serco: A survey of Steel and Zircaloy Corrosion Data for Use in the SMOGG Gas Generation Model, Report to NDA RWMD, SA/ENV-0841 Issue 3, 2010.

SELFRAC: Fractures and self-healing within the excavation disturbed zone in clays, final report, 5th EURATOM Framework Programme, European Commission Report EUR 22585, 2007.

Shaw, R.P.: Gas Generation and Migration, International Symposium and Workshop, 5th to 7th February 2013, Luxembourg, Proceedings FORGE Report, 2013.

Smailos, E.; Martínez-Esparanza, A.; Kursten, B.; Marx, G. and Azkarate, I.: Corrosion evaluation of metallic materials for long-lived HLW/spent fuel disposal containers. EUR 19112, European Commission, Luxemburg, 1999.

Small, J., Nykyri, M., Helin, M., Hovi, U., Sarlin, T. and Itävaara, M.: Experimental and Modelling Investigations of the Biogeochemistry of Gas Production from Low and Intermediate Level Radioactive Waste, Applied Geochemistry 23 (6), 1383–1418. doi:10.1016/j.apgeochem.2007.11.020, 2008.

SKB, Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. Technical report TR11-01, 2011.

Tsang, C.F., Barnichon J.D., Birkholzer, J., Li, X. L., Liu, H. H. and Sillen, X.: Coupled Thermo-Hydro-Mechanical Processes in the near Field of a High-Level Radioactive Waste Repository in Clay Formations., International Journal of Rock Mechanics and Mining Sciences, 2013.