Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 428–434

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Implications of safety requirements for the treatment of THMC processes in geological disposal systems for radioactive waste

Frédéric Bernier[a,*], Frank Lemy[b], Pierre De Cannière[a], Valéry Detilleux[b]

[a] Federal Agency for Nuclear Control (FANC), Brussels, 1000, Belgium
[b] Bel V, Brussels, 1070, Belgium

ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form
21 March 2017
Accepted 3 April 2017
Available online 15 April 2017

Keywords:
Radioactive waste
Geological disposal
Performance assessment
Safety assessment
Safety functions
Safety requirements

ABSTRACT

The mission of nuclear safety authorities in national radioactive waste disposal programmes is to ensure that people and the environment are protected against the hazards of ionising radiations emitted by the waste. It implies the establishment of safety requirements and the oversight of the activities of the waste management organisation in charge of implementing the programme. In Belgium, the safety requirements for geological disposal rest on the following principles: defence-in-depth, demonstrability and the radiation protection principles elaborated by the International Commission on Radiological Protection (ICRP). Applying these principles requires notably an appropriate identification and characterisation of the processes upon which the safety functions fulfilled by the disposal system rely and of the processes that may affect the system performance. Therefore, research and development (R&D) on safety-relevant thermo-hydro-mechanical-chemical (THMC) issues is important to build confidence in the safety assessment. This paper points out the key THMC processes that might influence radionuclide transport in a disposal system and its surrounding environment, considering the dynamic nature of these processes. Their nature and significance are expected to change according to prevailing internal and external conditions, which evolve from the repository construction phase to the whole heating–cooling cycle of decaying waste after closure. As these processes have a potential impact on safety, it is essential to identify and to understand them properly when developing a disposal concept to ensure compliance with relevant safety requirements. In particular, the investigation of THMC processes is needed to manage uncertainties. This includes the identification and characterisation of uncertainties as well as for the understanding of their safety-relevance. R&D may also be necessary to reduce uncertainties of which the magnitude does not allow demonstrating the safety of the disposal system.

1. Introduction

In the context of geological disposal of radioactive waste, the mission of the national regulatory body is to verify that the disposal system is developed, constructed, operated and closed in a safe manner, i.e. people and the environment are protected against the hazards of ionising radiations emitted by the disposed radioactive waste, without imposing undue burdens on future generations (Bernier and Lemy, 2013). This includes several types of activities such as the establishment of safety requirements as well as procedures and conditions for meeting these requirements for various stages of the licensing process (IAEA, 2011). The roles of the regulatory body include also the oversight of the activities of the organisation in charge of waste disposal and the review of the safety case and of its updates throughout the whole process of developing and implementing the geological disposal programme (Bernier and Lemy, 2013).

Safety requirements constitute a basis for the implementer to develop the disposal system, to conduct its research and development (R&D) programme, and to manage uncertainties. This paper discusses, from the regulatory perspective, the importance to study thermo-hydro-mechanical-chemical (THMC) processes to understand the disposal system behaviour at different stages of the disposal life cycle in order to build confidence in the safety case. It explains how R&D on these processes can contribute to the management of uncertainties being faced when assessing safety. Finally, the paper gives the main THMC processes that may influence

* Corresponding author.
E-mail address: frederic.bernier@fanc.fgov.be (F. Bernier).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2017.04.001

radionuclide transport in the disposal system and its surrounding environments.

2. The regulatory framework

The Belgian regulatory framework for radioactive waste disposal (Belgian Law, 1994; Belgian Royal Decree, 2001, 2011; AFCN, 2012) is underlain by two safety principles (the defence-in-depth and the demonstrability principles) and the radiation protection principles of ICRP (ICRP, 2007; Weiss et al., 2013). Besides, the regulatory body has also developed a set of requirements that the implementer has to fulfil in order to develop, construct, operate and close safely a disposal system.

2.1. Defence-in-depth principle

Defence-in-depth consists in a hierarchical deployment of different levels of protection in order to maintain the effectiveness of physical barriers placed between radioactive materials and workers, the public or the environment. Defence-in-depth is implemented through design and operation to provide a graded protection against a wide variety of transients, incidents and accidents, including equipment failures and human errors. The strategy for defence-in-depth is twofold: first, to prevent accidents and, second, if prevention fails, to limit their potential consequences and prevent any evolution to more serious conditions (IAEA, 1996).

When applied to the long-term safety of geological disposal systems, the defence-in-depth principle implies that the overall performance of the system shall not be unduly dependent on a single safety function (i.e. a specific purpose that must be accomplished by the disposal system for safety) (IAEA, 2011). Therefore, the disposal system has to be designed to prevent, as much as reasonably possible, that the integrity of components fulfilling a safety function can be jeopardised. Robustness, defined as the ability to fulfil the safety functions regardless of possible disturbances and construction contingencies, is also a key element of the defence-in-depth principle.

2.2. Demonstrability principle

The principle of demonstrability implies that the implementer of a disposal programme (Bernier and Lemy, 2013):

(1) demonstrates that the disposal facility can be constructed with the required level of performance (i.e. feasibility of its construction);
(2) uses proven techniques or new techniques based on qualification tests;
(3) demonstrates that the effective performance of the disposal system (i.e. as-built performance) allows to protect people and the environment against the hazards of ionising radiation despite all perturbations which might reasonably be envisaged and construction contingencies; and
(4) demonstrates that uncertainties are correctly managed.

2.3. Radiation protection principles of ICRP

The radiation protection system developed by the International Commission on Radiological Protection (ICRP) (ICRP, 2007; Weiss et al., 2013) is based on three key principles defined as follows:

(1) the principle of justification: Any decision that alters the radiation exposure situation should do more good than harm;
(2) the principle of optimisation of protection: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account the prevailing circumstances. When applied to the development and implementation of a geological disposal system, the principle of optimisation of protection has to be understood in the broadest sense as an iterative, systematic, and transparent evaluation of options for enhancing the protective capabilities of the system and for reducing radiological impacts; and
(3) the principle of application of dose limits: The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the dose limits.

2.4. Safety requirements

Most safety requirements included in the regulatory framework are derived from the safety and radiation protection principles described above. These requirements relate to the necessity to make provisions so that (1) potential radiological consequences for the population, the workers and the environment do not exceed the prescribed limits and are maintained as low as reasonably achievable; and (2) anticipated operational occurrences, accidents and failures are prevented and the resulting consequences are limited.

The development and implementation of a safety strategy is a key safety requirement. The safety strategy is intended to define the objectives and principles guiding the overall disposal programme. It has to be established at an early stage of the disposal system conceptualisation (IAEA, 2012). The safety strategy describes the mechanisms and methods used to achieve the safety targets and define how this strategy is implemented. It addresses a number of key elements such as optimisation of protection, defence-in-depth through the provision of multiple safety functions and of robust disposal system components, the containment and isolation of the waste and the demonstrability of safety-related features. It should also define the approach that will be followed to assess safety and manage uncertainties. The safety strategy will lead to the establishment of the safety concept defining performance targets for each safety function and component and their evolution in view of the hazards associated with the waste.

Safety requirements specific to the engineered barriers, the host rock and the site are also important elements to be considered by the implementer when developing the disposal system. According to the regulatory framework, the containment and isolation safety functions fulfilled by the disposal system should be ensured entirely by passive means after its closure. Due consideration should be given to processes and events that may disturb the disposal system during its construction and operation, and the induced consequences may affect post-closure safety. Furthermore, the engineered components of the system have to be physically and chemically compatible with each other, with the waste disposed of and with the host environment.

As a programme for characterisation of the environment surrounding the disposal system, the selected site and engineered barriers are needed in order to (WENRA, 2014):

(1) provide the information necessary to support the safety case;
(2) establish baseline conditions for the site;
(3) support the understanding of the expected system evolution;

(4) identify any events and processes associated with the site that might disturb the expected evolution of the disposal system; and
(5) support the understanding of the effect on safety of any features, events and processes associated with or challenging the disposal system.

Additionally, requirements related to safety assessment address the following topics:

(1) building confidence in the assessment;
(2) performance assessment (i.e. assessment of the ability of the system and of its components to fulfil their safety functions); and
(3) radiological impact assessment.

The necessity to establish confidence in the assessment derives directly from the demonstrability principle. This implies among others that (AFCN, 2012):

(1) the assessment rests on best available knowledge;
(2) the disposal system is well understood;
(3) the identification and treatment of features, events and processes are traceable and well-founded;
(4) a set of scenarios representative and bounding of the possible evolutions of the system is developed;
(5) models are shown to be appropriate to the objectives of the modelling through a justification, verification and validation process; and
(6) uncertainties are properly identified, characterised, analysed, treated and assessed.

2.5. Management of uncertainties

Decisions associated with a disposal programme are made in the presence of irreducible and reducible uncertainties. The management of both types of uncertainties is a key issue (Lemy and Bernier, 2013). Fig. 1 illustrates the typical and expected components of an uncertainty management strategy (Bernier and Lemy, 2013), including:

(1) the identification of the sources of uncertainties;
(2) their characterisation;
(3) the analysis of their potential relevance for safety;
(4) their treatment in the safety assessment; and
(5) the assessment of the need and possibility to avoid, reduce or mitigate uncertainties.

The analysis of safety relevance can lead to the exclusion of the uncertainty from further consideration, e.g. it can be demonstrated that the uncertainty on a particular parameter is not important to safety; the event/process can be shown to have a very low probability of occurrence. If not, the uncertainty needs to be "treated" by addressing the uncertainty explicitly, by bounding the uncertainty, or by using an agreed stylised approach to avoid addressing the uncertainty explicitly.

The management of uncertainties is an iterative process where R&D (including characterisation work) plays an important role. At the end of the process, uncertainties will inevitably remain but it should be demonstrated that these uncertainties do not undermine safety arguments.

3. Reasons for studying THMC processes

The knowledge of the initial state of the disposal system and the understanding of its possible evolutions are essential to perform and gain confidence in the safety assessment of disposal systems and the management of the uncertainties. More specifically, the identification and characterisation of the processes upon which the safety functions fulfilled by the disposal system rely, and of the processes that may affect its performance are key to developing scenarios describing possible evolutions of the disposal system and its environment (NEA, 2012).

THMC processes result from the coupling and mutual interactions among temperature gradients with heat flow (T), hydraulic pressure gradients with fluid flow (H), mechanical stresses with deformations (M), and chemical transport and reactions (C). Other processes such as gas generation and bacterial activity may also interact or be associated with these processes. The dynamic nature of THMC processes needs to be acknowledged and properly understood, as these processes are governed by changing conditions inside the disposal system, which evolve from the open-drift period to saturation period, and eventually through the whole heating–cooling cycle of decaying waste (Tsang et al., 2012). Varying external conditions such as loading and unloading processes to which the disposal system might be subjected (e.g. due to glaciation and erosion) will also contribute to the evolution of THMC processes within the system. THMC processes may influence radionuclide transport in the disposal system and its surrounding environment. It is therefore necessary to study the coupled THMC processes, and to understand their role in the behaviour of the disposal system. THMC processes could also be influenced by microbial activity. Indeed, if bacteria have sufficient space, water and nutrients, they can become active and alter the

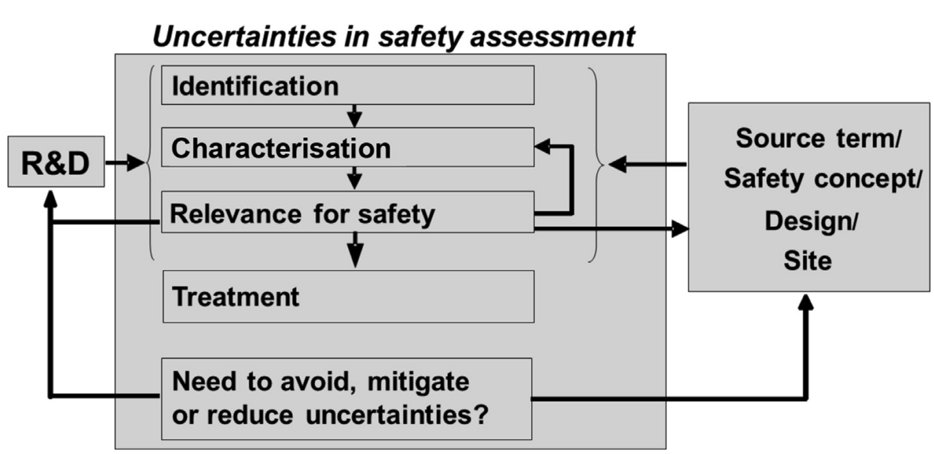

Fig. 1. Management of uncertainties (Bernier and Lemy, 2013).

performances of the disposal system (De Canniere and Meleshyn, 2013).

The implementer has therefore to develop a sound understanding of the safety-relevant phenomena to identify events and processes that may affect safety functions, and to assess possible impacts on radionuclide transport. This requires characterising the disposal system and its environment, developing, verifying and validating THMC models and managing associated uncertainties. The safety requirements constituting the regulatory framework are the starting point to develop the geological disposal system and therefore to define and conduct the R&D programme.

It is also important that the regulatory body maintains expertise in this field. Indeed, the independence of the regulatory body calls for the support from independent experts who develop and maintain the necessary know-how and skills in nuclear safety as well as in other safety-relevant scientific and technical fields. For complex issues such as those associated with the long-term safety of waste disposal facilities, this requires performing and/or coordinating R&D in support of safety analyses and inspections. R&D activities performed by the regulatory body are also necessary to build the credibility of its technical competence (a.o. vis-a-vis the civil society), integrity and judgement.

It is important to highlight that the objectives of regulatory body's R&D differ from those set up by waste management organisations. For instance, the regulatory body's R&D is mostly intended to investigate safety issues with the objective to assess if the safety concept developed by the waste management organisation fulfils the defined safety requirements. In that way, a special attention will be given to the identification of possible inadequate choices, assumptions, knowledge gaps, incompleteness, inconsistencies, mistakes (of reasoning or of implementation), etc., in the safety assessment of the waste management organisation. These activities are therefore more "a complement to" and "a verification of" than a "duplication of" the R&D activities performed by the implementer (SITEX, 2012). At the European level, organisations providing a technical and scientific support to regulatory decisions have developed a Strategic Research Agenda (SRA) (SITEX-II, 2016). This SRA includes R&D topics in relation to THMC processes.

4. THMC processes potentially relevant for safety

This section discusses THMC processes potentially relevant for safety when clayey host formations and/or engineered barriers are considered in the safety concept. Their relevance may vary according to several factors such as the characteristics of the source term, the safety functions on which the safety concept relies and the characteristics of the geological and engineered barriers fulfilling these functions. Safety functions assigned to clayey host formations and engineered barriers typically include the limitation of water advection and chemical retardation of radionuclides. Metallic and cementitious engineered components are also commonly considered to provide additional safety functions complementary to those fulfilled by geological components such as total containment of the waste contributing to the implementation of the defence-in-depth principle. The waste form may also fulfil a safety function in particular when waste processing is aimed at limiting the release of radionuclides under the conditions expected to prevail within the disposal system.

Various perturbations to disposal system components contributing to long-term safety will or may occur during the construction and operation of the disposal facility. Moreover, the performance of these components has to be compatible with the conditions prevailing in the host rock after construction and closure of the facility and on the long term. Engineered barrier alterations typically encompass concrete and clay degradation as well as metallic corrosion at different interfaces: waste/metal, waste/cement, cement/clay, metal/clay and cement/metal. The appropriate interfaces have also to be considered to assess the progressive dissolution and degradation of the different waste forms present in the waste inventory (e.g. spent fuel, glass, cementitious waste matrix, and bituminised waste). Furthermore, the host rock will be subjected to disturbances originating from the waste and the engineered barriers. Perturbations external to the disposal system such as glaciations, erosion processes and marine transgressions might also modify the conditions prevailing within the system as a result of internal perturbations.

Knowledge of the THMC characteristics of the host rock and of its geometry and depth is also fundamental for selecting an appropriate host formation and site. This includes characterising the uncertainties on these characteristics associated with their transferability from one site to another and from one host rock to another as an in-depth characterisation may not be available for each potential site.

After their migration through the host rock or the sealed shafts, a part of the radionuclides will eventually reach aquifers and the biosphere (i.e. the surrounding environment of the host rock). Although no containment function is assigned to geological formations in the surrounding environment of the host rock, a sufficient understanding of the transport in these formations and the biosphere is necessary to assess the hydrogeological and biosphere models used in the assessment of the radiological impact associated with the disposal facility.

4.1. Thermal (T) processes

High-level waste (HLW) and spent fuels emit residual heat due to radioactive decay. The thermal perturbation induced by heat-emitting wastes is likely one of the most important perturbations of the disposal system. The thermal load will induce different THMC couplings in the disposal system. For instance, it can affect the mineralogy and the porewater chemistry of a clayey formation and engineered barriers and hence their ability to retard radionuclide transport. Potential disturbances induced by a temperature increase in the disposal system include effects:

(1) on hydro-mechanical (HM) conditions (Tsang et al., 2012);
(2) on the stability and swelling properties of clay minerals (NEA, 2004);
(3) on the porewater composition (Beaucaire et al., 2012) and therefore on the chemical speciation, solubility and sorption properties of radionuclides;
(4) of flash pyrolysis of immature organic matter at 80 °C causing a rapid decarboxylation of the kerogen (i.e. solid and immobile organic matter presented in the clay) and the associated CO_2 release (in case of clay formations located at low to moderate depth without significant burial history) (Deniau et al., 2008; Lorant et al., 2008);
(5) of temperature gradient on the transport of water and solutes (Van Humbeeck et al., 2009);
(6) on the degradation of the concrete (stability of hydrated cement minerals); and
(7) on acceleration of the corrosion rate of the metallic barriers.

4.2. Hydraulic (H) and mechanical (M) processes

The early HM disturbances (together with thermal and chemical disturbances), created by the excavation during the operational phase and by the thermal load, might be the most severe transient processes that a disposal system will undergo on a large spatial scale. There is therefore a need to consider HM perturbations when assessing the temporal evolution of the overall disposal system to identify the relevant system conditions at the time when some radionuclides may be eventually released from the waste form.

HM perturbations may affect safety functions through a modification of the hydrogeological, geochemical, geomechanical and thermal conditions. HM perturbations may form a potential pathway for migration of radionuclides from the emplaced waste to the surface environment. This requires an evaluation of the characteristics and behaviour of the excavation disturbed or damaged zone (EDZ) for the time and conditions when radionuclide release actually might occur (Zuidema, 2005).

An important issue is the assessment of the combined effect of coupled HM processes due to the interactions among rock excavations, buffer emplacement, and the regional and local groundwater flow field at different spatio-temporal scales on the performance and safety of the disposal system. HM perturbations and possible future changes need to be assessed on a system-specific basis. The HM behaviour and related processes occurring and their magnitude need to be assessed in terms of post-closure performance considering the safety functions assigned to different system components and associated timeframes defined by the implementer in the safety concept.

The construction of the disposal facility represents a major perturbation, with the creation of new openings and new HM boundary conditions. The stress field is redistributed around the openings, and their surface is free to move inward until restrained by tunnel lining and support. The resulting rock deformations coupled with a low hydraulic conductivity induce deformations of the rock pore-space and porewater pressure changes. These changes can be either an increase or decrease depending on the location with respect to the locally redistributed stress field, and on the orientation of the opening with respect to the rock anisotropy (Tsang et al., 2012).

Tunnel ventilation and temperature changes may have a strong influence on rock properties, since they can cause desaturation in the near field. Desaturation, in turn, gives rise to capillary forces and hence an increase in rock cohesion and strengthening, while at the same time it increases tensile stress and the potential for bond failure (Tsang et al., 2012).

4.3. Bio-chemical (C) processes

4.3.1. Porewater chemistry and related processes

Porewater chemistry is a hot topic because porewater composition and the related physico-chemical parameters (pCO_2, pH, E_h) directly control transport processes occurring in a disposal system and influence HM processes. More specifically, porewater chemistry is essential to understand and predict the chemical speciation, the solubility and the sorption of radionuclides and to underpin migration studies. The knowledge of the porewater composition and the underlying geochemical and transport processes in clayey host rocks is thus an important part of the scientific basis required for safety assessment.

Hence, the control of perturbations (e.g. microbial perturbations) affecting the characterisation of in situ porewater chemistry such as the determination of pCO_2 under undisturbed conditions and also at elevated temperature for the case of heat-emitting waste is an important issue. The relevance for long-term safety of uncertainties associated with this determination may have to be analysed.

Porewater chemistry is also a key input to the studies aiming at understanding and assessing possible chemical perturbations of the waste forms and engineered barriers as these degradation processes will be mainly driven by porewater chemistry and water-solid phase interactions.

4.3.2. Clay oxidation

Clay oxidation can affect the performances of the host rock in the near field (oxidation front propagation) and those of the engineered barriers and the waste forms.

Different components of clayey rocks are very sensitive to oxidation by atmospheric oxygen available during excavation and ventilation of underground openings. The most sensitive component is pyrite (FeS_2), a common secondary sulfide mineral. Other sensitive components are organic matter and Fe(II)-containing phases, such as siderite ($FeCO_3$), Fe^{2+} sorbed in the cation exchange pool of clay minerals or associated to organic matter. Pyrite oxidation leads to the formation of iron oxy-hydroxides (FeOOH) and sulfuric acid (H_2SO_4) with the production of aggressive intermediate species such as thiosulfate ($S_2O_3^{2-}$). The porewater chemistry and the nature and the density of the electrical charges present at the surface of clay minerals are significantly modified by the drastic pH decrease caused by the release of sulfuric acid in the system.

4.3.3. Alkaline plume

The hyper-alkaline conditions imposed by the use of significant quantities of cementitious materials and the resulting alkaline plume in the near field could have an impact on the performance of clay barriers (Atkinson et al., 1985).

The alkaline plume could be accompanied by a loss of clay swelling properties and the formation of cracks (preferential pathways for water and radionuclides) in the buffer materials and the near field of disposal galleries. The transformation of smectite into illite or chlorite and the precipitation of calcite could also affect the self-sealing properties of clay materials (chemico-mechanical coupling).

4.3.4. Iron plume

Iron-clay materials can form at the interface between clay and metallic components. This process is sometimes called “iron plume” by analogy to the alkaline plume. The extension of the iron plume could affect the behaviour of a bentonite buffer (chloritisation of smectite by clogging of its interlayers with $Fe(OH)_2$ bridges) and its swelling ability.

4.3.5. Microbiological processes

The presence of organic matter in the waste, engineered barriers or host rock is a source of electron donor for bacteria and it can fuel the microbial activity if sufficient space and water are available in the system. Not only the small organic matter molecules produced by the kerogen oxidation can serve as electron donor, but also organic contaminants introduced by excavation and construction works and by human activities. Hydrogen generated by anaerobic corrosion of metals and water radiolysis induced by ionising radiations can also fuel the bacterial activity.

Bacterial activity can have both detrimental and positive effects on the performances of a geological disposal system by modifying the local chemical (C) conditions (Pearson et al., 2011; Stroes-Gascoyne et al., 2011). However, the potential positive effects on safety cannot be predicted with sufficient certainty and thus cannot be relied on, while potential harmful effects must certainly be analysed (Wersin et al., 2011). For example, sulfate-reducing bacteria (SRB) can produce sulfides or thiosulfates, both very aggressive chemical species inducing steel corrosion and therefore must be avoided in the immediate surrounding of steel canisters and overpacks. On the other hand, when consuming the hydrogen produced in the near field, bacteria could play a favourable role in decreasing the gas pressure, but this process remains highly uncertain especially if bacterial activity cannot develop due to space and water restrictions in the disposal system.

4.3.6. Gas generated by corrosion and water radiolysis

Gases will be generated in a disposal system. The main expected gas is hydrogen (H_2) which will be essentially produced by anaerobic corrosion of metals (Fe from steel overpacks and wastes and Zr from spent fuel zircaloy claddings) and by water radiolysis. If the gas generation rate exceeds the gas dissipation rate in the host formation and the engineered barriers, gas overpressure will develop. This could lead to gas breakthrough and to the formation of cracks or dilatational pathways which could represent preferential pathways for contaminated water and radionuclides to the aquifers and the biosphere. Gas overpressure could also push contaminated water further away through the barriers and act as a supplementary mechanism to enhance the radionuclide transport to the biosphere.

The thermal degradation of kerogen when present in the host formation and the decomposition of organic waste matrices will also produce CO_2 while reduction of nitrates that might migrate from bituminised wastes is expected to produce N_2 and N_2O gases. This will also contribute to the total gas pressure.

Possible modifications of the chemical conditions related to the reactivity of gases (mainly H_2 and CO_2) with engineered and geological barriers are also expected (FORGE, 2013).

5. Conclusions

Regulatory bodies are responsible for the establishment of a regulatory framework specifying the safety requirements and conditions for the development, operation and closure of disposal facilities. These requirements call for an appropriate understanding of the possible evolutions of the disposal system at different stages of its life cycle. THMC processes can potentially influence radionuclide transport in the disposal system and in its surrounding environment, as well as the ability of its components to fulfil their safety functions. It is therefore important to conduct a R&D programme dedicated to the identification and understanding of these processes and of their mutual interactions in order to assess the performance of the system as well as the events and processes that may affect the safety of the disposal. Such programme is a key element in identifying and characterising uncertainties regarding the evolution of the system and in developing an appropriate set of scenarios allowing assessment of long-term safety. R&D on THMC processes may also be needed to reduce uncertainties whose magnitude does not allow demonstrating the safety of the disposal system and is thus essential in building confidence in the safety assessment.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

The authors wish to express their grateful thanks to their colleagues Maryna Surkova, Benoit Guiot, Jeroen Mertens (FANC) and Pierre Janssen (Bel V) for their contributions and fruitful discussions in the process of elaborating the Strategic Research Agenda (SRA) of FANC – Bel V.

References

Atkinson A, Goult DJ, Hearne JA. An assessment of the long-term durability of concrete in radioactive waste repositories. MRS Online Proceedings Library 1985;50:239–46. http://dx.doi.org/10.1557/PROC-50-239.

Belgian Law. Loi du 15 avril 1994 relative à la protection de la population et de l'environnement contre les dangers résultant des rayonnements ionisants et relative à l'Agence Fédérale de Contrôle Nucléaire (AFCN). 1994 (in French).

Belgian Royal Decree. Arrêté Royal du 20 juillet 2001 portant sur le Règlement Général de la protection de la population, des travailleurs et de l'environnement contre le danger des rayonnements ionisants. Moniteur belge du 30 août 2001, tel que modifié (RGPRI-ARBIS). 2001 (in French).

Belgian Royal Decree. Arrêté Royal du 30 novembre 2011 portant prescriptions de sûreté des installations nucléaires. Moniteur Belge du 21 décembre 2011. 2011 (in French).

Beaucaire C, Tertre E, Ferrage E, Grenut B, Pronier S, Madé B. A thermodynamic model for the prediction of pore water composition of clayey rock at 25 and 80°C – comparison with results from hydrothermal alteration experiments. Chemical Geology 2012;334:62–76.

Bernier F, Lemy F. Implications of the regulatory framework and activities on R&D supporting repository implementation. In: Proceeding of the 2nd International Safety Case Symposium, The Safety Case for deep Geological Disposal of Radioactive Waste: 2013 State of the art. Radioactive Waste Management Committee; 2013. p. 69–74. https://www.oecd-nea.org/rwm/docs/2013/rwm-r2013-9.pdf.

De Canniere P, Meleshyn A. Microbial processes in a clay repository. In: Proceedings of EUROSAFE Forum 2013, Cologne, Germany; 2013. https://www.eurosafe-forum.org/sites/default/files/Eurosafe2013/Seminar%202/2.06_Microbial_Processes_Clay_Repository_FANC_GRS_Paper.pdf.

Deniau I, Devol-Brown I, Derenne S, Behar F, Largeau C. Comparison of the bulk geochemical features and thermal reactivity of kerogens from Mol (Boom Clay), Bure (Callovo–Oxfordian argillite) and Tournemire (Toarcian shales) underground research laboratories. Science of the Total Environment 2008;389(2–3):475–85. http://dx.doi.org/10.1016/j.scitotenv.2007.09.013.

Fate of Repository Gases (FORGE). European project funded by the European Union's 17th Framework Euratom Programme under grant agreement No. 230357. FORGE; 2013. https://www.bgs.ac.uk/forge/reports.html.

IAEA. Disposal of radioactive waste. IAEA specific safety requirements No. SSR-5. IAEA; 2011. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1449_web.pdf.

IAEA. The safety case and safety assessment for the disposal of radioactive waste, IAEA specific safety guide No. SSG-23. IAEA; 2012. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1553_web.pdf.

International Atomic Energy Agency (IAEA). Defence in depth in nuclear safety, INSAG-10, a report by the International nuclear safety Advisory Group. IAEA; 1996. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1013e_web.pdf.

International Commission on Radiological Protection (ICRP). The 2007 recommendations of the International commission on radiological protection. ICRP publication 103. Annals of the ICRP 2007;37(2–4). http://www.icrp.org/publication.asp?id=ICRP%20Publication%20103.

L'Agence Fédérale de Contrôle Nucléaire (AFCN). Projet de guide technique « Analyse de la sûreté post-fermeture des établissements de stockage définitif des déchets radioactifs ». Note externe 2012-02-28-FLE-5-4-4-FR, Rév. 0. Brussels, Belgium: AFCN; 2012 (in French).

Lemy F, Bernier F. Regulatory expectations regarding the safety case: moving from conceptualisation to implementation. In: Proceedings of EURADWASTE 2013, 8th EC Conference on the Management of Radioactive Waste Community Policy and Research on Disposal; 2013. p. 167–70. http://cordis.europa.eu/fp7/euratom-fission/docs/euradwaste-low.pdf.

Lorant F, Largeau C, Behar F, De Cannière P. Improved kinetic modeling of the early generation of CO_2 from the Boom Clay kerogen. Implications for simulation of CO_2 production upon disposal of high activity nuclear waste. Organic Geochemistry 2008;39(9):1294–301. http://dx.doi.org/10.1016/j.orggeochem.2008.05.008.

NEA. Methods for safety assessment of geological disposal facilities for radioactive waste: outcome of the NEA MeSA initiative. NEA; 2012. https://www.oecd-nea.org/rwm/reports/2012/nea6923-MESA-initiative.pdf.

Nuclear Energy Agency (NEA). Radioactive waste management: stability and buffering capacity of the geosphere for long-term isolation of radioactive waste: application to argillaceous media. NEA; 2004. https://www.oecd-nea.org/rwm/reports/2005/nea5303-stability-buffering.pdf#page=148.

Pearson FJ, Tournassat C, Gaucher EC. Biogeochemical processes in a clay formation in situ experiment: Part E – equilibrium controls on chemistry of pore water from the Opalinus Clay, Mont Terri Underground Research Laboratory, Switzerland. Applied Geochemistry 2011;26(6):990–1008. http://dx.doi.org/10.1016/j.apgeochem.2011.03.008.

SITEX-II. Horizon 2020, European Union Framework Programme for Research and Innovation. Draft D1.1 Strategic research agenda of the expertise function in the field of geological disposal of radioactive waste. SITEX-II; 2016. http://sitexproject.eu/index_2.html#deliverables.

Stroes-Gascoyne S, Sergeant C, Schippers A, Hamon CJ, Nèble S, Vesvres MH, Barsotti V, Poulain S, Le Marrec C. Biogeochemical processes in a clay formation in situ experiment: Part D – microbial analyses – synthesis of results. Applied Geochemistry 2011;26(6):980–9.

Sustainable network of independent technical expertise for radioactive waste disposal (SITEX). SITEX project deliverable D6.1: conditions for establishing a sustainable expertise network EC project. SITEX; 2012. http://sitexproject.eu/index_1.html#deliverables.

Tsang CF, Åkesson M, Barnichon JD, Jing L, Li XL, Schulze O. A combined review of key issues related to coupled THMC processes in the near-field of radioactive waste repositories in salt, clays and bentonite-crystalline rock systems. In: Proceedings of the European Commission TIMODAZ-THERESA International Conference: Impact of Thermo-hydro-mechanical-chemical (THMC) Processes on the Safety of Underground Radioactive Waste Repositories. European Commission; 2012. http://dx.doi.org/10.2777/2.

Van Humbeeck H, Verstricht J, Li XL, De Cannière P, Bernier F, Kursten B. The OPHELIE mock-up. Final report. EURIDICE report 09–134. 2009. http://www.euridice.be/sites/default/files/scientific/OPHELIE%20mock-up%20final%20report%20low%20resolution.pdf.

Weiss W, Larsson CM, McKenney C, Minon JP, Mobbs S, Schneider T, Umeki H, Hilden W, Pescatore C, Vesterlind M. ICRP Publication 122: radiological protection in geological disposal of long-lived solid radioactive waste. Annals of the ICRP 2013;42(3):1–57. http://www.icrp.org/publication.asp?id=ICRP%20Publication%20122.

Wersin P, Stroes-Gascoyne S, Pearson FJ, Tournassat C, Leupin OX, Schwyn B. Biogeochemical processes in a clay formation in situ experiment: Part G – key interpretations and conclusions. Implications for repository safety. Applied Geochemistry 2011;26(6):1023–34.

Western European Nuclear Regulators Association (WENRA). Report: radioactive waste disposal facilities safety reference levels. WENRA; 2014. http://www.wenra.org/media/filer_public/2015/03/18/srl_disposal_final_version_2014_12_22.pdf.

Zuidema P. The importance of the excavation damaged zone for post-closure safety of deep geological repositories: some introductory remarks. In: Proceedings of an European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories. Community Research and Development Information Service (CORDIS); 2005. https://cordis.europa.eu/pub/fp5-euratom/docs/edz-clusters-keynote_part1_en.doc.