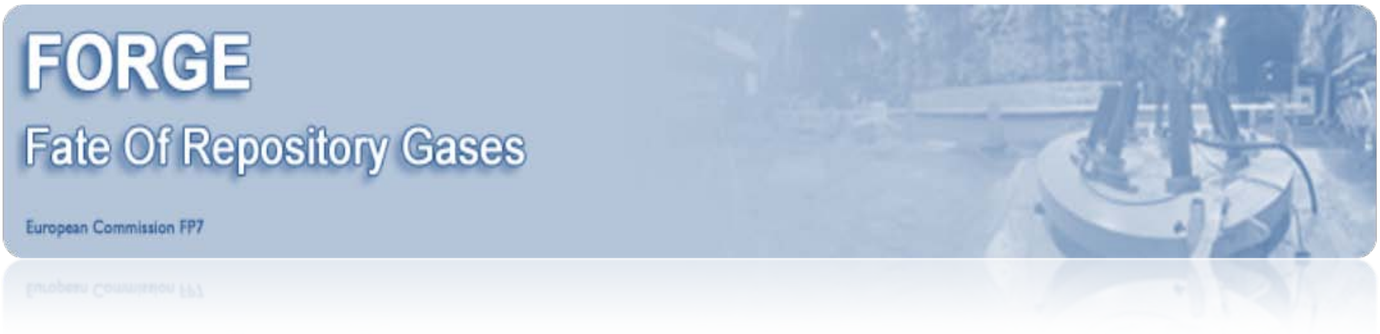

Principal outcomes of the FORGE – Fate of Repository Gases - Project

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Fate of repository gases (FORGE)

The multiple barrier concept is the cornerstone of all proposed schemes for underground disposal of radioactive wastes. The concept invokes a series of barriers, both engineered and natural, between the waste and the surface. Achieving this concept is the primary objective of all disposal programmes, from site appraisal and characterisation to repository design and construction. However, the performance of the repository as a whole (waste, buffer, engineering disturbed zone, host rock), and in particular its gas transport properties, are still poorly understood. Issues still to be adequately examined that relate to understanding basic processes include: dilational versus visco-capillary flow mechanisms; long-term integrity of seals, in particular gas flow along contacts; role of the EDZ as a conduit for preferential flow; laboratory to field up-scaling. Understanding gas generation and migration is thus vital in the quantitative assessment of repositories and is the focus of the research in this integrated, multi-disciplinary project. The FORGE project is a pan-European project with links to international radioactive waste management organisations, regulators and academia, specifically designed to tackle the key research issues associated with the generation and movement of repository gasses. Of particular importance are the long-term performance of bentonite buffers, plastic clays, indurated mudrocks and crystalline formations. Further experimental data are required to reduce uncertainty relating to the quantitative treatment of gas in performance assessment. FORGE will address these issues through a series of laboratory and field-scale experiments, including the development of new methods for up-scaling allowing the optimisation of concepts through detailed scenario analysis. The FORGE partners are committed to training and CPD through a broad portfolio of training opportunities and initiatives which form a significant part of the project.

Further details on the FORGE project and its outcomes can be accessed at www.FORGEproject.org.

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Contents

Summary

Understanding the behaviour of gases in the context of radioactive waste disposal was the focus of the FORGE Project. Of particular importance in the disposal of radioactive waste are the long-term performance of bentonite buffers, plastic clays, indurated mudrocks and crystalline formations. FORGE has provided experimental data to reduce uncertainty relating to the quantitative treatment of gas in performance assessment. This has been achieved through a series of laboratory, field-scale experiments (performed at a number of underground research laboratories throughout Europe) and modelling, including the development of new methods for up-scaling allowing the optimisation of concepts through detailed scenario analysis. It is important to understand a system to an adequate level of detail to allow confidence in the assessment of site performance, recognising that a robust treatment of uncertainty is desirable.

Introduction

The FORGE project is a pan-European project with links to international radioactive waste management organisations, regulators and academia, specifically designed to tackle the key research issues associated with the generation and movement of repository gasses with partners from 24 organisations in 12 European countries. It is supported by funding under the European Commission FP7 Euratom programme and started in February 2009 and ended in September 2013. Of particular importance are the long-term performance of bentonite buffers, plastic clays, indurated mudrocks and crystalline formations. Further experimental data are required to reduce uncertainty relating to the quantitative treatment of gas in performance assessment. FORGE has addressed these issues through a series of laboratory and field-scale experiments, including the development of new methods for up-scaling allowing the optimisation of concepts through detailed scenario analysis. The FORGE partners are committed to training and CPD through a broad portfolio of training opportunities and initiatives which form a significant part of the project.

The FORGE project was divided into five work packages.

- WP 1 Treatment of gas in performance assessment
- WP 2 Gas generation
- WP 3 Engineered barrier systems
- WP 4 Disturbed host rock formations
- WP 5 Undisturbed host rock formations

There are modelling activities in all of these work packages and a Modelling Co-ordinator specifically to overview all aspects of this work thus ensuring appropriate focus, facilitating the cross-flow of ideas and concepts between WP's is an integral part of the project. This also ensures best practice is shared between all participants and teams.

Various gases will be generated in a repository, including hydrogen (from metal corrosion) and methane and carbon dioxide (both from decomposition of organic materials contained in some wastes). Understanding where and how these gases form and how they move through the repository and surrounding rocks is the focus of the FORGE project. By using small scale laboratory experiments, large scale field tests (performed at a number of underground research laboratories throughout Europe), data and numerical modelling the results from FORGE is providing information to help guide repository design and predict future radionuclide migration.

The understanding and prediction of the evolution of repository systems over geological time scales requires a detailed knowledge of a series of highly-complex coupled processes. There remains significant uncertainty regarding the mechanisms and processes governing gas generation and migration in natural and engineered barrier systems. It is important to understand a system to an adequate level of detail to allow confidence in the assessment of site performance, recognising that a robust treatment of uncertainty is desirable. Of particular importance to the European radioactive waste management programmes are the long-term engineering performance of bentonite buffers, plastic clays, indurated mudrocks and crystalline formations. To reduce uncertainty, further experimental data are required to address:

- Corrosion and gas generation rates in repository environments;
- Key issues relating to the migration and fate of repository gases;
- Validation of numerical codes;
- Derivation of new methodologies for up-scaling from laboratory to field to repository scales;
- Optimisation of repository concepts through detailed scenario analysis.

FORGE has just ended and key results from the project are noted below.

Scientific results

Initial results of a series of long-term laboratory experiments to examine the mechanisms controlling gas flow and pathway sealing in the Callovo-Oxfordian Claystone (COx), the proposed host rock for the French repository, demonstrate that advective gas flow is accompanied by dilation of the samples (i.e. the formation of pressure induced micro-fissures) at gas pressures significantly below that of the minimum principal stress. Flow appears to occur through a local network of inherently unstable pathways, whose properties vary temporarily and spatially within the claystone. The coupling of parameters results in the development of significant time-dependent effects, impacting many aspects of COx behaviour, from gas breakthrough time, to the control of deformation processes. Variations in gas entry, breakthrough and steady-state pressures are indicative of microstructural heterogeneity which may exert an important control on the movement of gas.

As data continued to be acquired and understanding of these processes improves, a new conceptual model for advective gas flow in COx is beginning to emerge, one in which the onset of gas flow and the hydromechanical response of the material are integrally linked. The importance of pathway dilatancy during gas flow has now been clearly demonstrated and is driving the development of new experimentation to continue the development of the conceptual model for gas flow in COx.

Data collected during from a study of gas migration in bentonite clearly demonstrate a strong coupling between total stress, pore-pressure and applied gas pressure. In both tests so far completed, the evidence is for gas migration through the saturated bentonite by way of dilational pathways. This provides more evidence that, in some circumstances, gas flow through clay rich materials is at least partially through dilatants pathways.

In an initial set of tests, the general pressure and flow response in compacted bentonite (MX-80) and pure montmorillonite (Na- and Ca-form) due to externally applied water and gas pressure gradients was examined. A quite large number of different geometries and applied pressure ranges were explored. One of the main results of these tests is that they showed, very systematically, that the criterion for inducing breakthrough events – where the clay body is disrupted and the fluid flow increases by many orders of magnitude – is given by:

P≥P_ext

Where:

P denotes the total pressure of the sample

P_ext is the externally applied fluid (water or air) pressure.

Furthermore, the excess pressure required for breakthrough is shown to be dependent on both geometry and the type and density of clay.

Additional tests, where the pathways of the fluid during breakthrough were explored, showed that these usually follow the interface between clay body and test cell.

Recently, a set of "proof-of-concept" experiments have been performed in order to demonstrate the osmotic character of a saturated and confined swelling clay, and that this character governs the hydromechanical response. For example, gas breakthrough events have been induced by lowering the total pressure of the clay sample by flushing a highly concentrated salt solution on the opposite side, and the response due to pressurisation with kerosene – basically a non-polar liquid – have been shown to be very similar to the response due to gas pressurization.

A macroscopic model has been developed which treats confined bentonite as an osmotic system, taking into account the montmorillonite interlayers only (these pores dominates any compacted bentonite system). Within this approach the equations describing flow- pressure- and density response due to externally applied pressures have been deduced.

The theory has been successfully applied to several of the performed tests. In particular, the theory gives the same criterion for breakthrough events as found experimentally (see above), but also quantitative agreement is found e.g. for the water flow response due to applied water pressure gradients in an axial symmetric geometry, as illustrated in the figure below (test made on Na-montmorillonite of length 5 mm, and an initial swelling pressure of approximately 0.6 MPa).

One of the main conclusions arising from the theoretical work is that gas migration processes in bentonite are not a two-phase flow phenomena – i.e. gas is not replacing water in a static pore structure. Breakthrough events are, on the contrary, induced when gas dynamically "creates" its own volume by consolidating the clay body.

Experimental validation of critical stress theory applied to repository concepts has greatly increased our understanding and database of fracture flow properties. This study has highlighted the importance of stress-history on the flow properties of fractures because these systems display considerable hysteresis. Shearing has been seen to be a very effective self-sealing mechanism. Repeat gas injection testing has shown repeatability in “gas entry” values, but considerable differences have been seen in gas peak pressures.

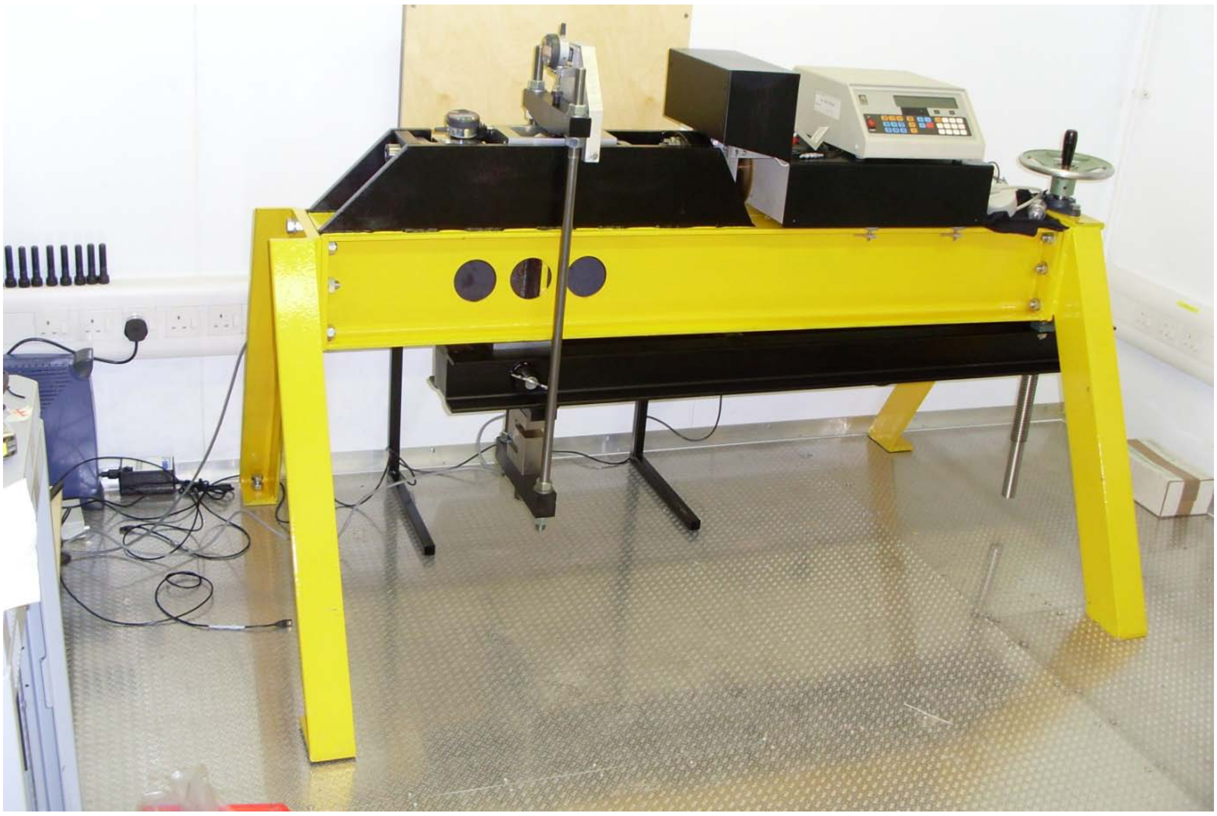

Figure 1: *Shear rig developed by the BGS as part of the FORGE Project to undertake experimentation into critical stress theory under well controlled experimental conditions (Photo - Rob Cuss; BGS).*

The effect of healing of the interfaces between manufactured bentonite blocks has been demonstrated by measuring the shear strength properties of the healed interface. The observation of significant cohesion confirms the “real” healing of the interface.

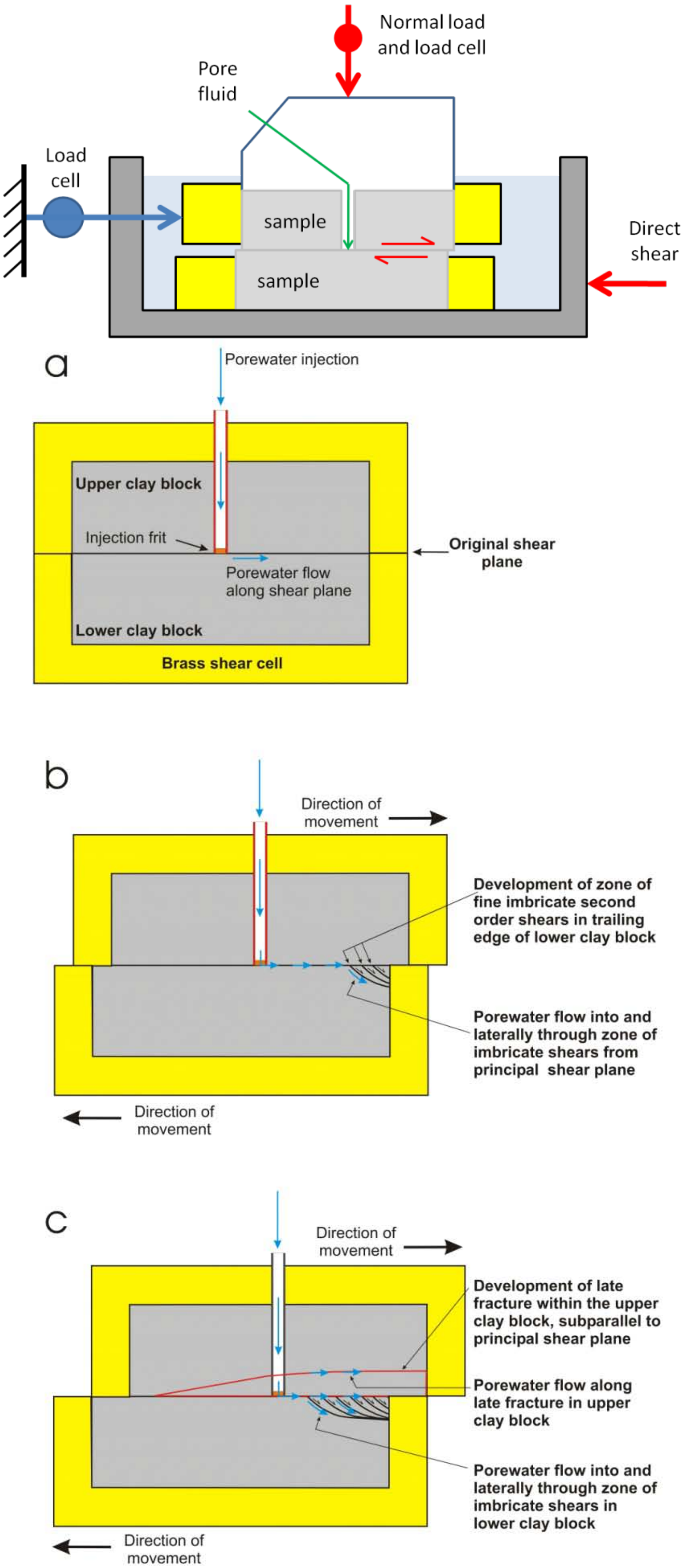

Figure 2: *Schematic of the direct shear rig (top) and schematic representation of the evolution of fractures developed in Opalinus Clay blocks undergoing sheer and porewater injection (bottom three images) (BGS).*

To ensure dissemination of information within the FORGE project and to interested stakeholders from outside the project annual meetings have been held. These have been held in locations that have enabled site visits to be made to URLs to allow participants to see some of the large scale experiments being undertaken by the project and to discuss their concepts, installation and results with the experimental teams.

Figure 3: *Participants at the second FORGE General Assembly hosted by the Czech Technical University in Prague after a visit the Josef underground research facility (Photo - CTU).*

Training

FORGE has organised two workshops, one on modelling and one on bentonite, each of two days duration and, in collaboration with Institute for Nuclear Research, Pitesti, Romania, provided a one week training course on Gas Migration in Geological Disposal Conditions. The course was attended by over 20 people including regulators, implementers and post graduate students form a number of countries including Italy, Korea, Romania, Bulgaria and the UK.

Figure 4: *Some of the participants attending the Gas Migration in Geological Disposal Conditions held at INR, Petisti, Romania discussing their practical bentonite hydration experiment (Photo - INR).*

Conclusions and Future work

Work undertaken in the FORGE project will benefit a range of customers via the provision of new information and understanding into the processes and mechanisms governing gas generation and migration. FORGE has also provided high-quality data that could be used for future activities such as benchmarking and validation of numerical codes for the quantitative prediction of gas flow, the development of HM (Hydrogeological – Mechanical) models for the prediction of EDZ and near-field processes and to assist in the assessment of the long-term evolution of the potential geological barriers.

The project has enhanced, in relation to the consideration of gas in safety case studies:

- Information and understanding;
- Methods, models and computer codes;
- Qualitative safety arguments;
- Quantitative assessments;
- Development and maintenance of expertise, collaboration.

Some gas-related uncertainties still remain, which is to be expected, and are already areas for further targeted work (e.g. CAST). Recognition and appropriate treatment of uncertainty is an important aspect of any safety case for the geological disposal of radioactive waste. Areas in which uncertainty may influence a safety case include:

- Uncertainty over future states of the system;
- Data uncertainty;

- Model uncertainty;
- Uncertainty about human behaviour.

Strategies have been developed to manage such uncertainties, ensuring that a safety case can be developed even given the presence of uncertainties. Such strategies consider:

- Demonstrating that the uncertainty is irrelevant:
  - e.g. safety controlled by other processes;
- Addressing the uncertainty explicitly:
  - representing by PDFs in a probabilistic calculation;
  - scoping effect of range of uncertainty by deterministic sensitivity calculations;
- Bounding the uncertainty:
  - making conservative assumptions;
- Ruling out the uncertainty on the basis of low probability;
- Explicitly ignoring uncertainty or agreeing a stylised approach for handling an irreducible uncertainty.

Gas-related uncertainties are not ‘show-stoppers’ in terms of adequate and appropriate consideration of gas in the safety case now; deployment of an approach to “Managing uncertainty” is a required component of any safety case, and is applicable to gas issues.

Overall Key Messages from FORGE are:

- Features, Events and Processes (FEPs) relevant to the consideration of gas in the safety case (the ‘gas issue’) are well-known, although therein there are uncertainties that need to be managed as a standard aspect of developing a safety case.
- Understanding the ‘gas issue’ provides coupled mitigation opportunities that can be considered on repository-specific basis, e.g. inventory optimisation, choice of materials for the Engineered Barrier System (EBS), repository design and repository operation (including repository sealing and closure).
- The relative importance of the ‘gas issue’ in the safety case is a function of the disposal concept under consideration, which is itself a function of the disposal inventory (including the gas source term, the approach to waste treatment and packaging, and how the packaged waste is management prior to emplacement in the repository etc) and the safety functions required to be provided by complementary barriers (e.g. EBS, geology).
- Repository-derived gas needs to be considered at an appropriate level in all repository safety cases. This can be done on the basis of existing knowledge.
- We have a sufficient understanding of the ‘gas issue’ now to be confident, on the basis of work undertaken in the EC FORGE project and complementary studies, that repository-derived gas presents no ‘show-stoppers’ to implementing geological disposal in a wide range of disposal systems.

Topics requiring further research include:

- In the case of cementitious environments, further study may be required for some conditions, e.g. changes to corrosion rates and associated gas generation rates influenced by:
  - pH changes and loss of carbon steel passivity;
  - Effect of organic degradation products.

- Microbial impacts on gas generation and migration were not examined by FORGE and issues where further (in situ) studies may be warranted are:
  - Microbial corrosion of steel and copper: not studied in FORGE, but considered in prior laboratory studies;
  - Utilisation of hydrogen as an electron donor by microbes (e.g. sulphate-reducing bacteria) - this process is normally conservatively ignored in assessing gas pressure build-up, but can reduce gas pressure.

- A detailed stress analysis is required to capture the transition from consolidation to dilatant pathway formation; effect is clearly geometry dependent, but other factors may be involved:
  - When the gas pressure reaches the sample pressure (e.g. as seen in LASGIT);
  - At an overpressure at about 20-30%;
  - At pressures 2-3 times higher than the sample pressure.

A Special Publication of the Geological Society is being edited to bring together the scientific papers presented at the meeting into a single volume as a resource for future researches in the field.

Acknowledgement

This report is based on the FORGE work package final reports.

With thanks to all FORGE partners for their contribution in developing the FORGE project and their effort over the last four and a half years working towards the successful outcome of the project.

Further details on the FORGE project and its outcomes can be accessed at www.FORGEproject.org. All reports arising from the project are published here and will remain accessible until at least 2019.

For more information on the project contact the co-ordinator at rps@bgs.ac.uk

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