Contractor Report to RWM
Sealing Deep Site Investigation
Boreholes:
Phase 2. Final Report
January 2018
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Sealing Deep Site Investigation Boreholes:
Phase 2. Final Report
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Preface

Radioactive Waste Management (RWM) carries out Research and Development (R&D) in support of geological disposal of the UK’s higher activity radioactive waste. The work presented in this report forms part of our R&D programme and was carried out by a consortium led by Amec Foster Wheeler on our behalf. The work has been reviewed by RWM and by two independent peer reviewers. RWM accepts the data and conclusions in this report.
Sealing Deep Site Investigation
Boreholes: Phase 2. Final Report

To: Radioactive Waste Management
Date: 23 March 2018
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Your Ref: RWM/03/046
Our Ref: 202580/14 Issue A
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23 March 2018

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Executive Summary

This report presents a summary of the work undertaken during a three year project (Sealing of deep site investigation boreholes: Phase 2) to develop generic approaches to seal deep boreholes drilled as part of site investigations at a potential Geological Disposal Facility (GDF) site.

The starting point of the project has been RWM's descriptions of illustrative geological environments potentially suitable for hosting a UK GDF and of illustrative designs for site investigation boreholes. Key features of the deep site investigation boreholes to be sealed are that they will be up to 2,000m deep and have a minimum diameter of 159 mm. Boreholes in Higher Strength Rock (HSR) are assumed not to require casing during their operational period, while casing is considered a contingency in both Lower Strength Sedimentary Rocks (LSSR) and evaporite horizons. In all cases, RWM's preferred approach and base-case assumption is that all casing is removed from the borehole prior to sealing; however, it is recognised that this may not always be possible, necessary or, from borehole stability considerations, desirable.

The Phase 2 project has been structured into a series of activities, or 'Tasks'. At the start of the project, these tasks were defined either as ‘Higher Priority’ or ‘Lower Priority’. Focus was placed on the former, which address issues that need to be resolved in order to demonstrate that suitable generic approaches to borehole sealing are available. The higher issues for generic research into borehole sealing are identified to be:

- to determine the functional requirements of borehole seals;
- to determine the standard of sealing that is likely to be required from the borehole seal, recognising that this will be uncertain at the generic stage;
- to determine the most appropriate seal concept and emplacement method for each generic geological environment, and to evaluate the advantages, disadvantages and risks associated with the different sealing concepts;
- to identify how the quality of the emplaced seals and support elements can be assured;
- to identify appropriate materials for post-closure support elements, taking into account mechanical stability and chemical interactions with adjacent seals.

Lower Priority tasks address issues where we believe suitable solutions are available from the existing or developing knowledge base, and where the requirement is to use this understanding in the context of borehole sealing. Lower activity tasks address issues relating to the borehole damage zone, aspects of the evolution and longevity of bentonite seals, aspects of borehole seals in evaporites and the application of analogues to borehole sealing.

In the project, we define the ‘borehole sealing system’ as being the overall system for sealing a site investigation borehole. In most instances, the borehole sealing system comprises a combination of ‘seals’ and ‘supports’, which fill the entire borehole. In some cases, short deformable metallic bridge plugs could potentially be used at the interface between seals and supports for a variety of purposes. Such bridge plugs would be formed from ductile metals expected to exhibit low corrosion behaviour when exposed to groundwater, as only such materials would ensure the integrity of the bridge plug over timescales of relevance to the Environmental Safety Case (ESC) for a GDF.

The borehole seal reduces groundwater flow (and in some circumstances, gas flow) through the borehole. The longevity of the seal will need to be commensurate with the timescale over which a reduction of flow through the borehole is required. Seals can be placed in the GDF host rock and in overlying (‘cover rocks’) or underlying rocks. The support elements fill the remainder of the borehole (except where bridge plugs might be placed), and provide mechanical support to the overlying seal, where present, in order to prevent the seal being damaged by movement within the borehole, and confinement to any underlying seal. This latter function is essential if the underlying seal is composed of bentonite, which exerts a swelling pressure and will increase in permeability if it is allowed to expand.
The main conclusions from the project are summarised below.

**Requirements for borehole sealing systems**

1. The required permeability of the borehole seal should be informed by the ESC rather than by a requirement to return the rock to its pre-drilled condition. The project has concluded that:
   a. from a GDF performance assessment perspective, borehole seals in HSR host rock need not have a permeability as low as that of the HSR itself. For example, the 2012 SKB Closure Report proposed the following design premise with respect to long-term safety for sealing of investigation holes at Forsmark: The resulting hydraulic conductivity over the length of the borehole shall be lower than $10^{-6}$ ms$^{-1}$;  
   b. in the case of LSR or evaporite host rocks, site-specific modelling of sites outside the UK undertaken by overseas Waste Management Organisations confirms that sealed boreholes can have hydraulic conductivities of up to $10^{-5}$ or $10^{-6}$ ms$^{-1}$ without significantly affecting radionuclide flux out of the geosphere.

2. In addition to the requirements from performance assessment, the borehole sealing system is required to protect groundwater resources from adjacent saline groundwater bodies and/or from overlying anthropogenic contamination.

3. The design of investigation boreholes at the site of a potential GDF, and of any long-term monitoring installations placed in them, should take account of the need for subsequent borehole sealing.

4. A tiered set of requirements for borehole sealing systems in generic geological environments has been developed. Higher level requirements must be fulfilled before lower level requirements are considered.
In practice, this implies a preference for:

a. concepts requiring only a limited number of steps for implementation;

b. demonstrated/proven emplacement techniques;

c. concepts in which the lengths of component sections (i.e. seal or support element) are long enough to ensure emplacement at the specified depths.

5. The modelling approach developed in the Phase 2 borehole sealing project should be used to explore optimisation of the arrangement of seals and support elements in a range of geological environments potentially relevant to RWM.

6. Gas migration through a sealed site investigation borehole is a potential concern only where the borehole intersects lower permeability cover rocks in a region where accumulation of GDF-derived gas is possible. In this case, the requirement is that the bentonite seal must fully re-saturate before the gas phase has migrated to the location of the borehole. This will influence the choice of the form of bentonite (high density block, pellet or slurry) selected for the seal.

Materials

7. Borehole seals in HSR and LSSR should be formed from bentonite.

a. High density bentonite blocks, pellets and slurries should all be considered as materials for forming borehole seals in HSR and LSSR. The optimum form of bentonite chosen to seal the borehole will depend on the geometry of the space to be sealed, the ease of emplacement and the required hydraulic conductivity of the borehole seal.

b. The hydraulic conductivity and swelling pressure of a bentonite seal will be controlled by the placed dry density of the bentonite, the proportion of swelling clay mineral in the bentonite and the composition of the groundwater in contact with the bentonite. These relationships can be used to determine which emplacement techniques and forms of bentonite (blocks, pellets, slurries) can achieve the required hydraulic conductivity for a borehole seal in a given groundwater composition.

c. That said, this report makes it clear that the standard of borehole sealing that can be achieved using bentonite pellets or blocks is likely to be significantly higher than required by the ESC. The laboratory experiments undertaken as part of this project show calculated hydraulic conductivities of less than $10^{-8}$ ms$^{-1}$ with seals formed from bentonite pellets, and of less than $10^{-11}$ ms$^{-1}$ with seals formed from bentonite blocks. These hydraulic conductivity values are very much lower than the acceptable hydraulic conductivities quoted in paragraph 1 for sealed boreholes in a range of geological environments. This indicates that borehole seals formed from bentonite are expected to yield hydraulic conductivities that are suitable for the purposes of borehole sealing.

Note that the bentonite pellets used in the tests reported here have not been optimised to maximise their placed density. The use of pellets with different shapes and sizes, including the use of pellets with a range of sizes, could result in different, and potentially greater, placed densities to those reported here. It is possible that significantly lower hydraulic conductivities could be achieved through optimising placed density.

d. Bentonite is susceptible to mechanical erosion by flowing groundwater. Therefore, it should not be used in higher permeability sections of borehole. Bentonite is also susceptible to chemical erosion in dilute groundwater. Such dilute groundwaters are unlikely to occur at GDF depth in potentially relevant geological environments under current UK climatic conditions. They might occur at GDF depth in some areas of the UK during future periods of glaciation. We recognise that EU-project BELBaR developed a better, and less cautious, representation of the processes that control bentonite erosion. Although this work was directed towards a better understanding of bentonite erosion in repository engineered barrier systems, the learning will also be relevant to understanding bentonite erosion in borehole seals. Note that there are no identifiable erosion vulnerabilities associated with any future increases in groundwater salinity.
8. Borehole seals in evaporite could be formed from natural evaporite minerals and/or from an appropriate cementitious formulation, such as salt-saturated cement or Sorel cement. Creep of halite around an uncased borehole will ensure long-term sealing against whatever materials are placed in the borehole. Before this occurs, natural materials such as crushed halite will not provide a low permeability seal; only cementitious materials can provide a low permeability seal during this period.

   a. The composition of borehole seals in evaporites (either formed from natural evaporite minerals or from salt-saturated cements) will depend on the site evaporite mineralogy; selection of materials for such seals should be left until the site-specific stage of the GDF siting programme.

   b. An appropriate cementitious formulation, such as salt cement or Sorel cement, should be used at the upper and lower boundaries of the halite formation to protect a borehole seal formed from halite until it has consolidated and achieved low permeability.

9. Three groups of materials suitable for support elements in HSR and LSSR have been identified. Selection of a support element material for a particular borehole can only be undertaken once site-specific and project-specific information is available.

   a. The following materials are considered suitable as supports in lower permeability sections of borehole: cementitious materials; granular materials (crushed rock, crushed rock-bentonite mixtures, bentonite-quartz mixtures and graded silica), and; barite-based materials.

   b. The following materials are considered suitable as supports in higher permeability sections of borehole: cementitious materials and coarse granular materials. The reason for omitting fine grained and unconsolidated (uncemented) materials is that erosion could be a problem. Graded silica that is formulated to behave as a Bingham Plastic may be suitable in high permeability sections of borehole, but further Research, Development and Demonstration (RDD) would be needed to demonstrate the conditions, if any, when it could be used.

Emplacement

10. Seal materials should be placed in direct contact with the rock. In cased boreholes, the casing will need to be removed, for example by localised milling, before the seal is placed.

11. Dump bailing is a very promising technique, because of its simplicity and reliability, and we recommend it should be used to place bentonite as blocks or pellets and to place support elements for use at locations where higher transmissivity features, such as fracture zones or permeable interbeds in the host rock, intersect the borehole. The project has identified that suitable dump bailers can, in theory, be developed for this purpose.

12. Bentonite slurry for borehole seals could be placed by conventional pumping using drill pipe, pumping using coiled tubing or by using dump bailers. The choice of technique will be influenced by factors such as borehole stability and the length of bentonite seal to be emplaced.

13. Longer sections of support materials for use in higher or lower permeability sections of borehole can be placed using conventional emplacement techniques used in the oil and gas industry.

Recommendations for borehole sealing systems

14. Recommendations for borehole sealing systems have been made for the three illustrative GDF host rocks (HSR, LSSR and evaporite) considered in the generic DSSC (gDSSC) and for any overlying cover rocks.

   The report concludes with recommendations for further generic RDD to enable RWM to demonstrate that generic approaches are available for sealing deep site investigation boreholes against groundwater flow and gas migration in a range of geological settings potentially relevant for a UK GDF.
# Abbreviations

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<tr>
<td>ANDRA</td>
<td>Agence nationale pour la gestion des déchets radioactifs</td>
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<td>API</td>
<td>American Petroleum Institute</td>
</tr>
<tr>
<td>BDZ</td>
<td>Borehole Damage Zone</td>
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<td>CCC</td>
<td>Critical Coagulation Concentration</td>
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<td>EA</td>
<td>Environment Agency</td>
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<tr>
<td>EBS</td>
<td>Engineered Barrier System</td>
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<td>EDZ</td>
<td>Excavation Disturbed Zone</td>
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<td>GDF</td>
<td>Geological Disposal Facility</td>
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<td>gDSSC</td>
<td>Generic Disposal System Safety Case</td>
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<td>HSR</td>
<td>Higher Strength Rocks</td>
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<td>IAEA</td>
<td>International Atomic Energy Agency</td>
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<td>ISE</td>
<td>Initial Site Evaluation</td>
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<td>LSSR</td>
<td>Lower Strength Sedimentary Rocks</td>
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<tr>
<td>NDA</td>
<td>Nuclear Decommissioning Authority</td>
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<tr>
<td>OPC</td>
<td>Ordinary Portland Cement</td>
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<tr>
<td>PA</td>
<td>Performance Assessment</td>
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<tr>
<td>RDD</td>
<td>Research, Development and Demonstration</td>
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<td>RWM</td>
<td>Radioactive Waste Management Ltd</td>
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<tr>
<td>QA/QC</td>
<td>Quality Assurance / Quality Control</td>
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<tr>
<td>QAP</td>
<td>Quality Assurance Programme</td>
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<tr>
<td>SKB</td>
<td>Svensk Kärnbranslehantering AB</td>
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<tr>
<td>UCS</td>
<td>Unconfined Compressive Strength</td>
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<tr>
<td>WIPP</td>
<td>Waste Isolation Pilot Plant</td>
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<td>WMO</td>
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1 Introduction

This is the final report from a three year project to develop generic approaches to seal boreholes drilled as part of investigations at the site of a potential Geological Disposal Facility (GDF). The project (Sealing of deep site investigation boreholes: Phase 2) is funded by Radioactive Waste Management (RWM) and undertaken by a team comprising of Amec Foster Wheeler, Bedrock Geosciences, Clay Technology, Galson Sciences, Nagra, Schlumberger and Quintessa.

The preceding phase of the project (Sealing of deep site investigation boreholes: Phase 1) was also undertaken by a team led by Amec Foster Wheeler, and identified the key issues for generic research into borehole sealing [1]:

► to determine the functional requirements of borehole seals;
► to determine the standard of sealing that is likely to be required from the borehole seal, recognising that this will be uncertain at the generic stage;
► to determine the most appropriate seal concept and emplacement method for each generic geological environment, and to evaluate the advantages, disadvantages and risks associated with the different sealing concepts;
► to identify how the quality of the emplaced seals and support elements can be assured;
► to identify appropriate materials for post-closure support elements, taking into account mechanical stability and chemical interactions with adjacent seals.

The preceding phase of the project also concluded that generic research into borehole sealing should focus on developing sealing concepts for Higher Strength Rock (HSR) and Lower Strength Sedimentary Rock (LSSR) environments [1]. The composition of seals in an evaporite environment was considered to depend on the site evaporite mineralogy, and would be addressed once a site is under consideration. These three illustrative geological environments, which are considered by RWM in the generic Disposal System Safety Case (gDSSC), are discussed in Section 2 of this report.

The Phase 2 project has been structured into a series of activities, or ‘Tasks’. At the start of the project, these tasks were defined either as ‘Higher Priority’ or ‘Lower Priority’. Focus was placed on the former, which address issues that need to be resolved in order to demonstrate that suitable generic approaches to borehole sealing are available. Lower Priority tasks address issues where we believe suitable solutions are available from the existing or developing knowledge base, and where the requirement is to use this understanding in the context of borehole sealing. The flowchart for higher priority tasks in the project is shown in Figure 1-1. Lower activity tasks address issues relating to the borehole damage zone (Task 13), aspects of the evolution and longevity of bentonite seals (Tasks 15/16), aspects of borehole seals in evaporites (Tasks 17/18) and the application of analogues to borehole sealing (Task 20).
The first part of this report (Sections 2 and 3) provides background information and describes the approach to borehole sealing and the functions and requirements placed on the various components in the borehole sealing system.

The main part of this report (Sections 4 to 11) presents the key conclusions from the Phase 2 borehole sealing project. The detailed technical work undertaken earlier in the Phase 1 and Phase 2 borehole sealing projects has already been reported and cross-references are given to these reports, which are listed in Table 1-1. Note that no published report has been produced for either Task 8 (‘complementary desk-based consultancy’) or Task 10 ‘(watching brief on international developments in Underground Research Laboratories (URLs)’). Work under Task 8 was reported through other tasks. A memorandum for RWM was produced under Task 10.

The third part of this report (Section 12) makes recommendations for generic borehole sealing systems in the geological environments relevant to RWM’s siting process for a GDF.

Overall conclusions from the project and areas where further Research, Development and Demonstration (RDD) is recommended are presented in Section 13. Key messages from the project are presented in boxes at the relevant points in individual chapters.

References are presented in Section 14. Note that in many cases, reference is made to the relevant technical reports produced as part of the borehole sealing project (references [1] to [14]). The reader should refer to these reports to obtain information on the primary references.

In this report, key points are highlighted in bold text within boxes. These boxes are not referenced from the text.
Table 1-1  Reports issued under Phase 2 of the Sealing of deep site investigation boreholes project

<table>
<thead>
<tr>
<th>Report title</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 2 borehole sealing project. FY 14/15 and FY 16/17. Issued on RWM bibliography (<a href="https://rwm.nda.gov.uk/publications">https://rwm.nda.gov.uk/publications</a>)</td>
<td></td>
</tr>
<tr>
<td>Annual Report for FY14/15 [2]. (Tasks 1 - 4)</td>
<td></td>
</tr>
<tr>
<td>Task 2b. Modelling the effects of site investigation boreholes on groundwater flow [3]</td>
<td></td>
</tr>
<tr>
<td>Task 5. Techniques used in the oil and gas industry for placing materials in boreholes. Potential application to generic sealing concepts for the RWM siting programme [4]</td>
<td></td>
</tr>
<tr>
<td>Task 6. Stage 1 laboratory programme [5]</td>
<td></td>
</tr>
<tr>
<td>Task 7. Stage 2 laboratory programme [6]</td>
<td></td>
</tr>
<tr>
<td>Task 9. QA/QC methodology for borehole sealing [7]</td>
<td></td>
</tr>
<tr>
<td>Task 11. Modelling the effects of different borehole sealing strategies on groundwater flow [8]</td>
<td></td>
</tr>
<tr>
<td>Task 12. Final report. This report</td>
<td></td>
</tr>
<tr>
<td>Task 13. Evolution of the borehole damage zone [10]</td>
<td></td>
</tr>
<tr>
<td>Tasks 15/16. Aspects of the evolution and longevity of bentonite seals [12]</td>
<td></td>
</tr>
<tr>
<td>Task 20. The use of natural, industrial and archaeological analogues in support of the borehole sealing project [14]</td>
<td></td>
</tr>
</tbody>
</table>
2 Illustrative geological environments and borehole designs

2.1 Introduction

RWM is undertaking R&D into borehole sealing because it expects that the Initial Site Evaluation\(^1\) (ISE) will require a clear description, supported by reference to R&D and technology demonstrations, of how site investigation boreholes might be sealed. The EA requirement is related to the integrity of the geological barrier at the site, and it derives from requirements given in Environment Agency Guidance on Requirements for Authorisation for Geological Disposal Facilities on Land for Solid Radioactive Wastes [15].

At the present time, the UK siting process for a GDF is at the generic stage; no sites are being investigated and there is no preferred geology. In this generic stage, RWM considers illustrative geological settings (host rock formations and associated geological and hydrogeological conditions) to develop generic disposal concepts [16, 17]. The three illustrative host rocks considered in the 2010 gDSSC are Higher Strength Rocks (HSR), Lower Strength Sedimentary Rocks (LSSR) and evaporites. LSSR and evaporite host rocks will be overlain by sedimentary cover rocks, and underlain by sedimentary rocks or basement rocks. Depending on their depths, boreholes might penetrate the rocks below the GDF host rock. HSR host rocks may either extend to surface or be overlain by sedimentary cover rocks. The illustrative geological settings are discussed further in RWM’s Geosphere Status Report [18], and are summarised in subsections 2.2 to 2.4.

2.2 Higher strength rock

HSR, which may be igneous, metamorphic or older sedimentary rocks, have a low matrix porosity and low permeability, with the majority of any groundwater movement confined to fractures within the rock mass.

HSR typically comprise crystalline igneous, metamorphic rocks or geologically older sedimentary rocks. Unweathered granite is a good example of a rock that would fall into this category. In geological terms, a rock mass comprising ‘higher strength rock’ might not be a single rock type in petrological terms, provided the different rocks present have similar mechanical properties (for example the different components of a composite igneous intrusion). In contrast, a bed of sedimentary HSR interlayered with weak and fractured beds would not be suitable. A key characteristic of higher strength rocks is that they are relatively brittle and will contain fractures, although these may be sealed by mineral growth.

HSR in a geological disposal context describes rocks which have high strength but low permeability and in which any appreciable radionuclide transport will be by groundwater advection through fractures (not all rocks that fall into the engineering classification of ‘high strength rocks’ meet the requirements for geological disposal). Because of the importance of fractures for fluid flow, permeability measured by field tests is usually much greater than that determined by laboratory tests on intact core samples. Higher strength rocks that exhibit significant bulk permeability would be unsuitable as host rocks unless an adjacent rock was able to provide isolation from the near-surface environment.

HSR host rocks as defined by RWM are being considered in Sweden, Finland and Canada as potential host rocks for deep geological disposal of higher activity radioactive wastes.

\(^1\) The ISE will be submitted by RWM to the Environment Agency (EA) as part of the process to obtain permission to start surface-based intrusive investigations
2.3 **Lower strength sedimentary rock**

Lower strength sedimentary rocks (LSSR) are fine-grained sedimentary rocks with a high content of clay minerals. They have low permeability and are mechanically weak, so that open fractures cannot be sustained. They will be interlayered with other sedimentary rock types. Although they have low permeability, LSSR may have significant water content in pores that are so small that water cannot flow through them. They are of interest both as potential host rocks and as potential seals providing additional containment above a GDF hosted in underlying rocks.

LSSR describes rocks which have low to moderate strength and contain a high proportion of clay. Any movement of water or dissolved chemical species is dominated by diffusion through the rock matrix because any fractures that develop in these rocks will self-seal. In the UK, this category includes clay and mudstone-dominated formations similar to the examples described in Section 3 of the 2016 Geosphere Status Report (RWM, 2017).

LSSR host rocks are being considered in France and Switzerland. Such rocks have sufficient strength to allow excavation of the GDF, provided that appropriate engineering support is provided. They may undergo brittle failure, but they are also able to creep to some degree so that fractures would not be able to act as flow paths in the long term.

2.4 **Evaporite**

Evaporite rocks have formed as ancient seas and lakes evaporated and often contain bodies of halite that provide a suitably dry environment and are weak and creep easily, so that open cracks cannot be sustained.

Evaporites are sedimentary rocks formed directly from the evaporation of surface water and commonly include abundant halite and beds of other minerals formed by evaporation, notably sulphate minerals. Other rock types present may include mudrocks, marls and dolomitic limestone. Halite merits a distinct safety case because it provides a dry environment that will not be infiltrated by water and because any cracks will be self-sealing over timescales appropriate to geological disposal. Halite may occur as layers (beds), or may have been mobilised in the subsurface to form large diapirs or domes of halite that penetrate younger formations. An analogous safety case is not applicable to other evaporite rocks or minerals (such as dolomite or anhydrite), because these may contain water and would not have the required self-sealing properties.

In halite formations, the absence of mobile groundwater means that there is no groundwater pathway and limited potential for gas generation, provided that water ingress does not occur. Hence, the importance of sealing any penetrations into the halite formation.

A potential suitable evaporite host rock for a GDF will be overlain by cover rocks containing LSSR.

The Waste Isolation Pilot Plant (WIPP) in USA is currently being operated in a bedded halite host rock.

Salt domes do not occur within the area of interest for the UK GDF siting programme (herein England, Wales and Northern Ireland), so an evaporite host rock would be a bedded halite formation.

2.5 **Illustrative properties of generic host rocks**

Some indicative properties of the generic host rocks described in subsections 2.2 to 2.4 are presented in [19] and reproduced in Table 2-1. Illustrative groundwater compositions for potentially relevant geological environments (that is, combinations of host rocks and cover rocks) are also presented in [19] and reproduced in Table 2-2. In this report, it is sufficient to consider the overall salinity, pH and redox potential of the groundwater; note that the salinity ranges given in Table 2-2 are wide, and reflect that RWM is currently at an early stage in the GDF siting process.
<table>
<thead>
<tr>
<th>Property</th>
<th>Higher-strength host rock</th>
<th>Lower-strength Sedimentary Rock</th>
<th>Evaporite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity and fluid flow</td>
<td>Flow is predominately through fractures in the rock, and the hydraulic conductivity is therefore heterogeneous and scale dependent. Bulk hydraulic conductivity is in range $10^{-13}$ m/s to $10^{-6}$ m/s.</td>
<td>Any fluid movement is predominantly through the rock mass itself. Hydraulic conductivity is in the range $10^{-15}$ m/s to $10^{-3}$ m/s parallel to bedding. The value perpendicular to the bedding may be up to a factor of 100 lower.</td>
<td>Flow is negligible</td>
</tr>
<tr>
<td>Porosity</td>
<td>Fractured rock can be represented as a dual porosity system, with matrix porosity in the range 0.0001 – 0.05, and a significantly lower value for the effective transport porosity</td>
<td>0.05 to 0.4</td>
<td>0.00 – 0.04 Undisturbed halite is likely to have a connected porosity of effectively zero, although there may be inclusions of fluid on the micron to mm-scale</td>
</tr>
<tr>
<td>Solute transport</td>
<td>May be predominantly by advection in fractures, although diffusion into the matrix will retard solute transport</td>
<td>Assumed to be predominately by diffusion</td>
<td>Any transport is likely to be by diffusion via heterogeneities (e.g. clay or anhydrite interbeds)</td>
</tr>
<tr>
<td>Mechanical strength and excavation stability</td>
<td>High mechanical strength, e.g. 100 MPa - 325 MPa Unconfined Compressive Strength Excavations could be self-supporting in sparsely fractured volumes</td>
<td>Low to medium mechanical strength, e.g. 12 MPa - 100 MPa Unconfined Compressive Strength Excavations are likely to require support</td>
<td>Low to medium mechanical strength, e.g. 12 MPa - 30 MPa Unconfined Compressive Strength Excavations could be self-supporting</td>
</tr>
<tr>
<td>Deformation behaviour, and possibility of self-sealing EDZ.</td>
<td>Brittle. Any Excavation Disturbed Zone (EDZ) created during construction will not seal by deformation</td>
<td>Plastic. Any EDZ will partially seal by deformation</td>
<td>Exhibits rock creep. Any EDZ can be expected to recover by deformation</td>
</tr>
<tr>
<td>Thermal conductivity and heat tolerance</td>
<td>Medium thermal conductivity in range 2.2 W m$^{-1}$ K$^{-1}$ – 3.8 W m$^{-1}$ K$^{-1}$</td>
<td>Relatively low thermal conductivity: 0.6 W m$^{-1}$ K$^{-1}$ – 3.2 W m$^{-1}$ K$^{-1}$ in the horizontal direction and 0.6 W m$^{-1}$ K$^{-1}$ – 1.9 W m$^{-1}$ K$^{-1}$ in the vertical direction. Temperature significantly above 100 °C may lead to changes to mineralisation</td>
<td>Relatively high thermal conductivity, 3.5 W m$^{-1}$ K$^{-1}$ – 6 W m$^{-1}$ K$^{-1}$ (4) and high tolerance to heat (e.g. 200 °C temperature limit)</td>
</tr>
<tr>
<td>Sorption behaviour</td>
<td>Moderately strong sorption to rock surfaces</td>
<td>Strong sorption to rock surfaces</td>
<td>Limited potential for sorption to evaporite</td>
</tr>
<tr>
<td>Gas transport properties</td>
<td>Low gas-entry pressure into open fractures, meaning transport in a gas phase is possible</td>
<td>High gas-entry pressure, meaning transport in a gas phase is less likely than for HSR. Gas may be released through pore dilation and micro-fissuring in the clay</td>
<td>High gas-entry pressure</td>
</tr>
</tbody>
</table>
Table 2-2  Illustrative groundwater compositions in host rocks in generic geological environments (from [19])

<table>
<thead>
<tr>
<th>Geological environment</th>
<th>Total dissolved solids (mgL$^{-1}$)</th>
<th>pH</th>
<th>Redox potential (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSR to surface</td>
<td>1,000 - 40,000</td>
<td>6 – 9</td>
<td>-400 mV to +300 mV. Eh negative at any potential GDF location</td>
</tr>
<tr>
<td>HSR overlain by higher permeability sedimentary rocks</td>
<td>15 - 265,000. Highest value corresponds to halite-saturated basinal brine; depends on presence of overlying sediments containing evaporite minerals</td>
<td>5 – 9</td>
<td>-400 mV to +300 mV. Eh negative at any potential GDF location</td>
</tr>
<tr>
<td>HSR overlain by lower permeability sedimentary rocks</td>
<td>10,000 - 265,000. Highest value corresponds to halite-saturated basinal brine; depends on presence of overlying sediments containing evaporite minerals</td>
<td>5 – 9</td>
<td>-400 mV to +300 mV. Eh negative at any potential GDF location</td>
</tr>
<tr>
<td>LSSR overlain by higher permeability sedimentary rocks</td>
<td>500 - 265,000. Most likely a few thousand to a few tens of thousands of mgL$^{-1}$. Higher values where clays in contact with overlying sediments containing evaporite minerals, or where LSSR contains evaporite minerals</td>
<td>6.5 - 9</td>
<td>-350 mV to +500 mV, but most likely to be reducing</td>
</tr>
<tr>
<td>LSSR overlain by lower permeability sedimentary rocks</td>
<td>500 - 265,000. As above, higher values occur where clays are in contact with overlying sediments containing evaporite minerals, or where LSSR contains evaporite minerals</td>
<td>6.5 - 9</td>
<td>-350 mV to +500 mV, but most likely to be reducing</td>
</tr>
<tr>
<td>Bedded halite overlain by sedimentary sequence</td>
<td>265,000 - 365,000. Corresponds to halite saturation at 20°C and 60°C</td>
<td>6.5 – 7.5</td>
<td>-350 mV to -100 mV</td>
</tr>
</tbody>
</table>

2.6 Illustrative borehole designs

RWM’s Site Characterisation Status report [20] presents assumptions about the scope of site characterisation activities and the features of site investigation boreholes. A subsequent RWM workshop [21] considered the factors influencing borehole design and developed illustrative borehole designs and high level drilling sequence programmes. Based on these RWM illustrative designs, we list below a series of assumptions regarding the design of generic site investigation boreholes that will require sealing:

- depths ranging from 100m to 2,000m;
- minimum open hole diameter will be $6\frac{1}{4}$” (159 mm); maximum open hole diameter will be 36” (914 mm) although, in the upper part of the borehole, 26” (660 mm) would be more typical;
- boreholes deviate from the vertical by less than 45-50°;
- no casing is considered necessary in HSR; in contrast, 7” casing is considered as a contingency for both LSSR and evaporites. The overburden in overlying rocks is always assumed to require casing;
- casing will be of standard American Petroleum Institute (API) carbon steel.

Finally, in order to minimise the potential impact of site investigation boreholes on the post-closure performance of the GDF, RWM’s site characterisation designs will keep the extent of
exploratory drilling in the immediate vicinity of a proposed GDF to a minimum, consistent with providing adequate characterisation of the site.

However, it should be noted that in some geological environments it will be necessary to drill at least some boreholes close to the potential GDF footprint in order to adequately characterise the site and develop engineering designs and the Environmental Safety Case (ESC). In addition, at the time when initial site investigation boreholes are drilled, there could be some uncertainty regarding the final location of the GDF. Hence, although the intent may be to locate site investigation boreholes remote from the final GDF footprint, this is unlikely to be achieved in all geological environments. When a sealing system is developed for a specific site characterisation borehole, proximity to the GDF is one of the attributes of the borehole that must be considered when defining its performance requirements.

2.7 The geometry of the borehole section to be sealed

The geometry of the section of borehole to be sealed is a key consideration when selecting the form of material for the seal. In subsection 5.2, it will be shown that bentonite is the preferred material for forming a borehole seal, and that the bentonite could potentially be placed in the borehole as high density blocks, pellets (a type of granular material) or slurries. The main issue is that some forms of materials, such as pellets and slurries, can fill irregular voids whilst other materials, such as blocks, cannot. The choice of which form of bentonite to use is therefore influenced by the shape of the void to be filled.

Experience of drilling boreholes in HSR shows that it is possible, with good drilling practice, to form boreholes that are in-gauge over most of their length. In contrast, boreholes in LSSR generally show significant variation in diameter along their length. An example is shown in Figure 4.2 of [7], where enlargements greater than 500 mm are evident in a nominal 100 mm borehole.

Geomechanical modelling and borehole stability analysis to illustrate borehole geometry and depths of damage in a range of rocks of potential relevance to RWM is presented in Section 8 of [2]. The modelling considered five rock types based upon rock strengths, and their likely associated stress regimes in the UK. The analyses predicted the enlargement of the boreholes if all yielded (i.e., damaged, inelastic) material in the borehole walls was removed, resulting in an over-gauge/broken-out hole.

The modelling demonstrated\(^2\) that boreholes in very strong metamorphic and igneous rocks (Unconfined Compressive Strength (UCS) > 100 MPa) can be expected to remain in-gauge, with little risk of a shear-induced Borehole Damage Zone (BDZ) in the intact material. At the other end of the spectrum, boreholes in mudrocks and other weak sedimentary formations (UCS < 12.5 MPa) are expected to show break-out and over-gauge hole / potential damage zones over most of the borehole length; approximately 80% if drilled at balance\(^3\). The calculated modal enlargement is 20%.

The comparison is shown in Figure 2-1; the reader should focus on the borehole stability information, shown as the yellow shading in the figure. ‘Wellbore damage’ is extensive in the case of the LSSR (lower figure). There is no wellbore damage in the case of the HSR (upper figure). The modelling illustrates that boreholes drilled in some geological environments of interest to RWM are expected to show significant variability in borehole diameter (‘rugosity’).

\(^2\) Note that this analysis does not consider the creation of any other potential BDZ, for example as a result of the disturbance of any natural fracture systems.

\(^3\) Balanced drilling is a procedure used to drill boreholes where the pressure in the wellbore is kept equal to the static pressure of the formation being drilled.
Figure 2-1  Illustrative borehole stability analyses. Comparison of predicted wellbore damage (shown in yellow) in Higher Strength Rock (modelled as UCS > 100 MPa) (above) and Lower Strength Sedimentary Rock (next page)
Figure 2-1 continued. Illustrative borehole stability analyses. Comparison of predicted wellbore damage (shown in yellow) in HSR (previous page) and Lower Strength Sedimentary Rock (modelled as UCS < 12.5 MPa) (above)
3 The approach to borehole sealing

3.1 Introduction

An open borehole provides negligible resistance to water flow along the borehole\(^4\). If an open borehole connects two or more transmissive features\(^5\), it will form a transmissive connection between them. See Figure 3-1, in which groundwater flows to the borehole in one feature and away from the borehole in another feature. Such flows would occur if the ‘undisturbed’ groundwater heads in the features are different, which would usually be the case.

![Figure 3-1](image)

**Figure 3-1** Flows as a result of a borehole linking two transmissive features (groundwater head being higher in the lower feature)

In the context of geological disposal of radioactive waste, the issue is that groundwater containing radionuclides derived from the waste within the GDF may flow into a site investigation borehole, and return to the biosphere on shorter timescales than would otherwise occur. In order to mitigate or prevent this effect (which is illustrated in Figure 3-1), it is envisaged that site investigation boreholes would be sealed once any measurements to be made in the boreholes have been completed. In the remainder of this section, we review approaches to borehole sealing in a range of industries and describe the components of the borehole sealing system and their safety functions.

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\(^4\) In subsequent modelling, we represent an open borehole as having a hydraulic conductivity of \(1 \times 10^{-3} \text{ ms}^{-1}\).

\(^5\) A transmissive feature might be a transmissive fracture, a transmissive fracture zone or a very permeable rock formation.
3.2 Review of approaches to borehole sealing

A review of approaches to borehole sealing in a range of industries was conducted as part of the Phase 1 borehole sealing project, and is reported in Section 4 of [1]. The industries reviewed were: nuclear, in the context of deep geological disposal of higher activity radioactive waste; oil and gas (‘conventional’ reserves, not fracking); CO₂ storage, and; water resources. The approach to sealing boreholes is broadly consistent across these industries, although this is sometimes obscured by the different nomenclatures used. The main common themes are:

sections of boreholes are sealed to prevent or reduce to an acceptable degree the movement of fluids through the borehole for as long as is required. Seals must have sufficiently low permeability and sufficient longevity to meet these requirements. The required length of time varies between the industries and countries considered, and this greatly influences the choice of material for the seal;

seals (described alternatively as ‘key zones’ and ‘primary seals’ in the reports reviewed) are placed across lower permeability sections of rock in uncased sections of borehole. Their lengths depend on the rock properties and sealing concept; 30m or more is typical. Working in conjunction with the surrounding rock, they restrict fluid movement along the borehole. Seals are not placed directly across high permeability horizons;

some or all the intervals between the seals are filled with materials (described as ‘plugs’, ‘backfill’ etc. in the various reports reviewed) that provide mechanical stability for the surrounding rock and overlying and underlying seals;

lengths of cemented casing often remain in the borehole, as a result of cost considerations and/or practicability of removing the casing. Casing is locally milled out to enable borehole seals to be placed directly in contact with the rock.

3.3 Components of the borehole sealing system

Based on the above review and on initial work undertaken by RWM before the start of the Sealing of deep site investigation boreholes project [22], we propose below that the main components of a borehole sealing system, which we define as the overall system for sealing a site investigation borehole, are ‘seals’ and ‘supports’. In most instances, the borehole sealing system comprises a combination of these two components.

Seal. The borehole seal reduces groundwater flow (and in some circumstances, gas flow) through the borehole. The longevity of the seal will need to be commensurate with the timescale over which a reduction of flow through the borehole is required. Seals can be placed in the GDF host rock and in overlying (‘cover rocks’) or underlying rocks.

Support. The support elements fill the remainder of the borehole, with the exception of any locations at which ‘bridge plugs’ are placed; see below for details. The support element provides mechanical support to any overlying seal, in order to prevent the seal being damaged by movement within the borehole, and confinement to any underlying seal. This latter function is essential if the underlying seal is composed of bentonite, which exerts a swelling pressure and will increase in permeability if it is allowed to expand. Supports are required in three situations:

at locations where higher transmissivity features, such as fracture zones or permeable interbeds in the host rock, intersect the borehole. Such features are of limited vertical extent in the borehole, and could occur in both the host rock and any cover rocks;

in intervals where lower permeability rock intersect the borehole, and where the lower permeability rock does not need to be sealed throughout its thickness in order to achieve the required overall standard of sealing. This might be sections of the GDF host rock that do not

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6 Borehole sealing approaches in the three generic host rocks considered by RWM in the 2010 gDSSC were reviewed.
require sealing or sections of the overlying or underlying rocks; in longer intervals where higher permeability rock units intersect the borehole. This could occur in sections of rocks overlying or underlying the GDF host rock. By definition, extensive sections of high permeability rock will not occur within the GDF host rock.

Figure 3-2 illustrates the use of support elements across higher transmissivity features and in adjacent higher permeability rocks. Modelling that considers the optimum disposition of seals and supports in a borehole within HSR is presented in subsection 4.5.

The required length of the borehole seal will be informed by a number of issues:

- the seal will need to be of sufficient length to achieve its objectives;
- the seal will need to be of sufficient length to withstand any differential pressure applied across it;
- the seal will need to be of sufficient length that uncertainties in depth of placement do not compromise its performance;
- the seal will need to be of sufficient length that it is not ‘bypassed’ by flow in the local rock around it (a particular issue for HSR).

Given the above, a minimum length of several tens of meters is considered appropriate, unless constrained by the presence of an adjacent higher transmissivity feature. The actual length of the borehole seal should be justified as part of the design process.
In addition to these two components, short deformable plugs (termed ‘bridge plugs’\(^7\)) could potentially be used at the interface between seals and supports for any of three purposes:

- as a means of confining bentonite seals (particularly, shorter seals) to prevent them swelling before the overlying support element has attained sufficient strength. In this context, a bridge plug is a variety of support element;
- to isolate a seal from the adjacent support, should there be any concerns about the spatial extent of chemical reaction between the two components;
- for Quality Assurance / Quality Control (QA/QC) purposes, to provide a precise and accurate depth in the borehole (for example, on which to place a seal) if this could not be achieved by the technique used to place material in the borehole.

Such bridge plugs would be formed from ductile metals expected to exhibit low corrosion behaviour when exposed to groundwater, as only such materials would ensure the integrity of the bridge plug over timescales of relevance to the ESC for a GDF.

Figure 3-3 Potential flow paths for a section of sealed borehole

Regarding the borehole sealing system itself, we define four potential flow pathways, as illustrated in Figure 3-3:

- flow through the borehole seal;
- flow along the boundary between the seal and the surrounding rock (the ‘annulus’, should there be any shrinkage of the seal away from the borehole wall);

\(^7\) The term ‘bridge plug’ is standard terminology. The potential applications that are envisaged for the bridge plug in this report are wider than are used in the oil and gas industry. The use of ‘plug’ should not be taken to imply a specific purpose for this device.
flow in a damaged zone of rock immediately surrounding the borehole (the ‘Borehole Damage Zone (BDZ)’);

flow in the undisturbed rock around the borehole.

As is clear from Figure 3-3, the permeability of the borehole sealing system at the time of sealing is a function of the permeability of the borehole seal, of the interface between the seal and the surrounding rock, and of the surrounding BDZ.

### 3.4 Safety functions of the borehole sealing system

The geosphere contributes to the two principal safety objectives for a GDF – the isolation of the wastes and the containment of radionuclides in the wastes.

**Geological isolation.** Isolation is achieved by placing the waste deep underground in a location lacking potential resources and with all access routes to the GDF backfilled and sealed. This shields humans in the surface environment from external irradiation and considerably reduces the risks of both intentional and inadvertent human disturbances and intrusion.

**Geological containment.** The geological environment also provides containment by preventing or delaying and attenuating the releases to the biosphere of any radionuclides and non-radioactive chemo-toxic contaminants from the GDF. The geosphere can fulfil its containment role in different ways. In the case of an evaporite, the key feature is the virtual absence of water as a transport medium. In many other geological settings, it is the slow movement of groundwater and geochemical retardation or immobilisation that ensure long travel times and consequent radioactive decay for any radionuclides released from a GDF.

The safety function of the borehole seal is to reduce groundwater flow (and, in some circumstances, gas flow) through the sealed borehole for as long as is required to ensure that the borehole does not compromise the ‘geological containment objective’ of the geosphere. The ‘geological containment objective’ could be compromised in all geological environments by a site investigation borehole that acts to provide a ‘short circuit’ for groundwater flow from the GDF to the biosphere. In addition, in a halite host rock, site investigation boreholes that penetrate the host rock must be sealed to prevent ingress of groundwater into the halite with potential subsequent dissolution of the host rock and loss of containment.

The safety function of borehole supports is to provide mechanical support and confinement to any overlying and underlying seals such that each adjacent seal achieves the design requirements over its lifetime.

In addition to these safety functions, which are derived from considerations of post-closure performance of the GDF, there are two additional functions for components of the borehole sealing system:

- supports are required to protect borehole seals from damage during emplacement that arises from inflows or outflows to the borehole through adjacent higher transmissivity features;
- the borehole sealing system is required to protect groundwater resources from adjacent saline groundwater bodies and/or from overlying anthropogenic contamination. Guidance from the environment agencies, who are the regulators in the devolved administrations responsible for protecting groundwater resources, was discussed in subsection 4.5.1 of [1].

The boreholes considered in this report are up to up to 2,000m deep and may encounter a range of geological, hydrogeological and hydrogeochemical conditions. Given this, and the requirements of the GDF safety case and of groundwater resource protection legislation, it is possible that the design of seals will vary from one location in a borehole to another. As described in subsection 3.3, support elements are required for three situations in the borehole. Different designs and materials will probably be required for the different types of support elements.
3.5 Requirements for a borehole sealing system

Requirements for borehole sealing systems in generic geological environments were presented in Section 9 of [2]. An updated set of requirements, which includes consideration of support elements, is illustrated in Figure 3-4 and discussed below. Higher level requirements must be fulfilled before lower level requirements are considered.

The required permeability of the borehole seal should be informed by the environmental safety case for the GDF rather than by a requirement to return the rock to its pre-drilled condition.

In addition to requirements arising from GDF performance, the borehole sealing system is required to protect groundwater resources from adjacent saline groundwater bodies and/or from overlying anthropogenic contamination.

Given the range of geological, hydrogeological and hydrogeochemical conditions that may be encountered in a borehole, and the requirements above, design of seals may vary from one location in a borehole to another. Different designs and materials will probably be required for the different types of support elements.

![Figure 3-4 Requirements for a borehole sealing system in a generic geological environment](image-url)
The first requirement is that the components of the borehole sealing system (seals and supports) must achieve the design properties at emplacement. The required permeability of the borehole seal will be informed by the environmental safety case rather than by a requirement to return the rock to its pre-drilled condition. This is discussed further in Section 4. Permeability requirements on borehole support elements are limited to short-term reductions in groundwater flow sufficient to enable seals to be placed without damage and to protect groundwater resources from saline water bodies and anthropogenic contamination.

The second requirement concerns the longevity of the components of the borehole sealing system. The environmental safety case for a GDF considers a timescale to 1 Ma post closure, so reduction of groundwater flow through the borehole over this period will be required. It is important to note that the required standard of sealing will decrease with time as the hazard from the radionuclide inventory decreases due to radioactive decay. Seal performance in relation to GDF-derived gas movement also needs consideration in some borehole locations, to mitigate the possibility of the migration of radioactive gases produced in the GDF. The upper timescale for such sealing will be of order of 50,000 years (approximately ten half-lives of C-14). These timescales are very long compared to timescales considered when sealing boreholes for conventional groundwater resource protection. See discussion in subsection 4.5.1 of [1].

Erosion of seals by cross-flow in the borehole during emplacement can be prevented by use of appropriate emplacement techniques. Erosion of seals after emplacement can be prevented by defining the limiting values for parameters such as groundwater velocity and groundwater chemistry, which control the onset of any erosion in the seal material, and ensuring that seals are only placed in sections of borehole where erosion after emplacement will not be an issue.

To achieve the required longevity, seal materials will need to be resistant to erosion and physical and chemical degradation in the sections of borehole where they are to be used, as these processes could, if extensive, result in an increase in hydraulic conductivity that is sufficient to compromise the longer-term performance of the seal. In the case of the support element, the key requirements are that the material will not consolidate or settle over these timescales, and will develop sufficient compressive strength to adequately confine any overlying or underlying seal. In addition, chemical interactions of the support element with an adjacent seal should not occur to an extent that compromises the performance of the seal on long timescales.

The third requirement is that the borehole sealing system can be emplaced in accordance with the design. It will therefore be necessary to demonstrate that borehole seals/supports are emplaced correctly and achieve the design intent. The more onerous the design requirements, the more challenging it will be to demonstrate that this has been achieved. From the perspective of demonstrating compliance, there is merit in adopting sealing solutions that are more straightforward to emplace and for which emplacement technologies are tried and tested. In practice this implies:

- a preference for concepts requiring only a limited number of steps for implementation;
- a preference for demonstrated/proven emplacement techniques;
- a preference for concepts with long sections of similar materials, as short sections may be more difficult to emplace at specified depths.

The fourth requirement, once the previous requirements have been met, is that the cost of the borehole sealing system is optimised. The principal cost is likely to be associated with the emplacement of the seals and supports in the borehole. The method of emplacing the materials (discussed in Section 6 of this report) and the arrangement of seals and supports (which controls the number of separate operations required) are the main cost components.
3.6 Preparing boreholes for sealing

RWM’s illustrative approach to preparing boreholes for sealing is presented in Section 5 of [22], and is summarised below.

3.6.1 Removal of installed equipment and other downhole equipment

RWM’s illustrative approach is that equipment installed within the borehole is either removed or pushed to a sufficient depth such that it could not influence radionuclide migration from a GDF [22]. To ensure this, borehole seals would have to be placed above the equipment. To facilitate removal of any installed borehole equipment, detailed records of the installation and its design should be kept.

3.6.2 Casing removal and cementation

Removal

The two main reasons for inserting casings in boreholes drilled to characterise a potential GDF site are likely to be:

- to support unstable rock around the borehole, and;
- to prevent cross-flow through the borehole, which would perturb measured groundwater heads and could result in degradation of groundwater resources.

The driver for wishing to remove the casing is that the cement bond between the casing and the surrounding rock will degrade in the longer term; certainly within the timescale of relevance to the ESC. Therefore, the approach taken by the Phase 2 Borehole Sealing project is that borehole seals must be placed in direct contact with the rock in order to be effective on these long timescales. Borehole sealing for groundwater protection purposes considers much shorter timescales, and this is presumably the reason why guidance for achieving groundwater protection is that removal of borehole casing is only to be considered ‘where the casing has corroded or broken, or the grouting has failed’. See discussion in subsection 4.5.1 of [1].

Prior to the Sealing Deep Site Investigation Boreholes project, RWM’s base-case concept [22] was that all casing is removed from the borehole prior to sealing. This approach is consistent with recommendations in a 1990 International Atomic Energy Agency (IAEA) technical report on approaches to seal boreholes, tunnels, and shafts associated with radioactive waste repositories [23]. The difficulty in removing all casing was recognised both by the IAEA and RWM.

We consider that removing all of the borehole casing may not be practicable or desirable, as removal of the casing in areas of unstable ground could result in further breakouts and even borehole collapse. This would increase the size and permeability of the BDZ. From Figure 3-3, it would be detrimental to the overall performance of the borehole sealing system if the enlarged BDZ became the most significant of the flow pathways through or around the sealed borehole. Further, based on borehole-specific considerations, it may be unnecessary to remove casing in some sections of the borehole where support elements are to be placed because, even after degradation of the casing, there would be no significant impact on GDF performance.

Therefore, RWM describe ‘alternative’ assumptions for their illustrative sealing concepts in which some casing is left in the borehole. It is important to emphasise that, even in each ‘alternative assumption’ (there is one for each illustrative borehole design), all casing is removed from sections of the borehole where seals are to be emplaced.

If sections of casing are to be removed, it will be necessary to mill out or ‘overwash’ the casing to allow a borehole seal to be placed in direct contact with the rock. In the oil and gas industry, this would generally involve milling at least 30m (more often 50m) of casing, then under-reaming.

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8 ‘Over-washing’ casing involves milling the outer surface of the casing with a larger diameter circular hollow mill until the casing can be retrieved.
to remove old cement and damaged rock\(^9\). A similar approach is envisaged to place seals in boreholes around a GDF.

**Cementation of casing**

Steel casing that is left in place will not provide a long-term low permeability barrier to groundwater flow along the borehole, even if the cement bond between the casing and the wallrock is good at the time of borehole sealing. Notwithstanding this, it is good practice within the oil and gas industry to re-evaluate the quality of the casing cementation before the borehole is sealed, and to improve the quality of cementation if it is considered inadequate. This is partly to reduce the permeability of any annular gap between casing and rock in the short to medium term, but also to enable the permeability of borehole seals to be estimated in downhole pressure tests. Approaches to improving cementation are described in subsection 4.3.4 of [1] and subsection 5.7 of [7]. As with installed equipment, detailed records of the casing system should be kept to increase the likelihood of successful casing removal.

3.6.3 **Borehole reaming**

Although under-reaming undertaken during local milling of casing may expose or even remove some fresh rock, this is not its primary purpose. It was noted in subsection 4.3.4 of [1] that reaming out the damaged rock around the borehole in order to remove or reduce the BDZ or to re-establish a cylindrical geometry in a borehole section containing breakouts is likely to lead to further breakout and rock damage. There may be circumstances where it would be justified to ream out the BDZ, for example if it had grown substantially over time, but this would need to be carefully considered.

3.6.4 **Cleaning out the borehole to remove debris and borehole wall cake**

Cleaning out the borehole to remove debris and borehole wall cake will be undertaken prior to installing the borehole sealing system. This will enable a reliable bond to be achieved between borehole wall and the sealing or support materials. Mechanical, chemical and hydraulic technologies may be used to achieve a clean wellbore prior to seal emplacement. Introduction of chemicals into the borehole will need approval from the environmental regulator.

3.6.5 **Borehole condition surveys**

As a minimum, a caliper survey will be required before the borehole is sealed, in order to determine any changes to borehole dimensions that have occurred since drilling and to derive a volume estimate for the borehole sections to be sealed. In addition, a survey of borehole trajectory is required to ensure the location of the sealed borehole is established. The various types of caliper surveys available are discussed in more detail in [7]. The caliper log should be run with a gamma log to enable control of reference depths in comparison with earlier logs.

If casing is to remain in the borehole, the standard of cementation should be determined. A number of wireline tools are available to assess seal and cement quality in cased borehole environments. Cement bond logs and ultrasonic imaging tools, as discussed in subsection 4.3.8 of [1], have been available for many years and are used extensively across the oil and gas industry.

If the borehole has been open for a long period of time before sealing and if there are concerns that the BDZ may be a significant pathway for groundwater movement around the borehole seals (but see subsections 4.2 and 5.1, which emphasise that this will not be the case in most situations), then further characterisation of the BDZ would be required. Combinations of resistivity, sonic logs and calliper tools are normally employed in oil and gas wells to identify and assess the different aspects of mechanical damage to the borehole during drilling and with time.

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\(^9\) Under-reaming involves enlarging a wellbore past its original drilled size.
The need for additional surveys will depend on the scope of testing during site characterisation. If hydrogeological testing of lower permeability formations has not been undertaken during site characterisation, it will probably be necessary to further characterise the permeability of zones in which borehole seals are to be placed. It may also be appropriate to determine the location of any saline transition zone before sealing, to characterise the geochemical environment in which the seals are to be placed.
4 What is the required permeability of a sealed borehole?

4.1 Introduction

Post-closure safety for a GDF is achieved through multiple barriers: the waste package, the engineered barrier system (EBS) and the geosphere. Different geological disposal concepts place different requirements on these barriers, and assume different relative contributions from package, EBS and geosphere to overall radionuclide containment.

‘Geological containment’ relates to containment of radionuclides released from a GDF, not to containment of groundwater. When a potential site for a GDF has been identified and a disposal concept selected, it will be possible to calculate the impact that site characterisation boreholes would have on radionuclide transport, and to determine the permeability and longevity of seals commensurate with achieving the required degree of geological containment. However, at the present generic stage of the UK GDF siting programme, neither site nor disposal concept (which influences the timing and extent of radionuclide release from a GDF) have been selected.

Therefore, in the Sealing Deep Site Investigation Boreholes project, three approaches were used to estimate the likely permeability required of a sealed borehole in HSR, LSSR and halite GDF host rocks:

- 1D analytical calculations of groundwater flow in and surrounding a borehole, which are presented in Section 6.2 of [1]. The objective is to demonstrate, for the range of geosphere parameter values presented in Section 3 of [1], where the principal resistances to flow might occur. The required permeability of a borehole seal relative to the permeability of the surrounding rocks and the BDZ is informed by these calculations;

- review of previous work undertaken by other radioactive waste management organisations (WMOs) to evaluate required standards of sealing for site investigation boreholes, which is presented in Section 6 of [2]. The review presents site-specific examples where the effects of open or sealed boreholes on groundwater flow or radionuclide transport have been calculated. Examples from HSR, LSSR and evaporites (halite) are presented;

- numerical modelling of the impact of site investigation boreholes sealed to different standards (spanning the range from an open borehole to a borehole sealed throughout its length with bentonite) on groundwater flow rates and flow paths in illustrative HSR environments. The study is reported in [3]. HSR was chosen for the study as the output from the approaches above indicated that site investigation boreholes in HSR had the greatest potential to impact geosphere containment. LSSR and evaporite (in the context of RWM’s siting programme, ‘evaporite’ is taken to be equivalent to bedded halite) environments were not modelled because in such host rocks we would expect groundwater flow to be very low or non-existent. In LSSR, radionuclide transport through the surrounding rocks to a sealed borehole is diffusion-controlled; halite does not contain mobile groundwater.

The conclusions from these studies are summarised in subsections 4.2 to 4.4.

4.2 1D analytical calculations of groundwater flow

The analytical model comprises three flow resistances arranged in series, and is discussed in more detail in subsection 6.2 of [1]:

- flow to the borehole through a transmissive feature in the surrounding rock;
- flow along the borehole;
- flow away from the borehole through a transmissive feature in the surrounding rock.
Flow along and around the borehole is represented by the four pathways represented in Figure 3-3, which are considered as flow resistances arranged in parallel. Table 4-1 to Table 4-3 present parameter values taken from the numerical modelling study described in subsection 4.1. Table 4-4 presents the hydraulic resistances for the various pathways through and around a borehole seal in HSR calculated, using the same approach as used for the earlier Phase 1 borehole sealing study, from the parameter values in Table 4-1 to Table 4-3.

Table 4-1   Illustrative groundwater flow properties of HSR. Taken from [19] and used in modelling undertaken by the project [3]

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>HSR in near-surface</th>
<th>HSR at depth</th>
<th>Minor fracture zones</th>
<th>Local fracture zones</th>
<th>Regional fracture zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity k (ms⁻¹)</td>
<td>3.2 E-8</td>
<td>1.8 E-10</td>
<td>1.0 E-8</td>
<td>1.0 E-8</td>
<td>1.0 E-7</td>
</tr>
<tr>
<td>Thickness of fracture zones L (m)</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4-2   Representation of the borehole seals in the model. Taken from [3]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bentonite seal</th>
<th>Granular seal</th>
<th>No seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity k (ms⁻¹)</td>
<td>1.0 E-10</td>
<td>1.0 E-5</td>
<td>1.0 E-1</td>
</tr>
</tbody>
</table>

Table 4-3   Hydraulic conductivity of the annulus and BDZ in the model (borehole diameter is 160 mm). Units of ms⁻¹. Taken from [3]

<table>
<thead>
<tr>
<th>Component</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annulus</td>
<td>1.0 E-09 (equivalent to fracture of uniform aperture 10 µm)</td>
</tr>
<tr>
<td>Borehole Disturbed Zone in HSR at depth</td>
<td>1.8 E-09 (i.e. ten times k of rock layer)</td>
</tr>
</tbody>
</table>

Table 4-4   Calculations of flow resistance. Pathway properties as in Table 4-1 to Table 4-3

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Property</th>
<th>Flow resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Fracture Zone</td>
<td>Transmissivity (m²s⁻¹)</td>
<td>1 E+07 sm⁻²</td>
</tr>
<tr>
<td>Local Fracture Zone</td>
<td>Transmissivity (m²s⁻¹)</td>
<td>1 E+06 sm⁻²</td>
</tr>
<tr>
<td>Regional fracture zone</td>
<td>Transmissivity (m²s⁻¹)</td>
<td>1 E+05 sm⁻²</td>
</tr>
<tr>
<td>HSR at depth</td>
<td>Hydraulic conductivity (ms⁻¹)</td>
<td>2 E+09 sm⁻²</td>
</tr>
<tr>
<td>Seal (bentonite)</td>
<td>Hydraulic conductivity (ms⁻¹)</td>
<td>2 E+14 sm⁻²</td>
</tr>
<tr>
<td>Seal (granular)</td>
<td>Hydraulic conductivity (ms⁻¹)</td>
<td>2 E+09 sm⁻²</td>
</tr>
<tr>
<td>Open borehole</td>
<td>Hydraulic conductivity (ms⁻¹)</td>
<td>2 E+05 sm⁻²</td>
</tr>
<tr>
<td>BDZ in HSR at depth</td>
<td>Hydraulic conductivity (ms⁻¹)</td>
<td>8 E+12 sm⁻²</td>
</tr>
<tr>
<td>Annulus</td>
<td>Hydraulic conductivity (ms⁻¹)</td>
<td>8 E+12 sm⁻²</td>
</tr>
</tbody>
</table>

The main points to note from these calculations are:

flow resistances associated with flows into and out of the borehole from fracture zones in the surrounding HSR are much smaller than resistances associated with flows along the sealed borehole. That is, for the parameter ranges considered above, flows through the sealed

borehole are controlled by whichever of the seal, annulus, BDZ or surrounding undisturbed rock has the lowest flow resistance; comparison of the various flow resistances along the borehole show that, for the parameter values chosen, flow resistance of a bentonite seal is 25 times higher than that of the BDZ. Further, the flow resistance of the bentonite seal is five orders of magnitude greater than that of the undisturbed rock around the borehole. When the borehole seal is represented as a granular material, the scoping calculations indicate that the flow resistance of the undisturbed rock and the seal are equal, and both are now 4,000 times lower than that of the BDZ.

The scoping calculations demonstrate that the hydraulic conductivity of the borehole seal must be significantly greater than that of the undisturbed rock before the borehole seal becomes the dominant flow pathway. Also, more flow may take place through the BDZ than the borehole seal if the latter is of very low permeability; however, significantly more flow is likely to take place through the surrounding rock than through the either the BDZ or borehole seal.

4.3 Literature review

The principal conclusion of the review is that seals with permeabilities significantly higher than those of the surrounding rock are still likely to be acceptable in many cases from a post-closure safety perspective. For example:

- for higher strength host rocks, where hydraulic conductivity over a scale of tens of metres is typically in the range $10^{-8}$ to $10^{-13}$ m$^{-1}$ s$^{-1}$ (Table 2-1) and where fracture zones could be of order $10^{-5}$ m$^{-1}$, recent modelling for SKB indicated that a sealed borehole at Forsmark would need to have hydraulic conductivity greater than $10^{-4}$ m$^{-1}$ s$^{-1}$ in order to have a significant impact on transport pathways [24]. Given these results, the 2012 SKB Closure Report [25] concluded that the design premise with respect to long-term safety for sealing of investigation holes could be relaxed. A new design premise was proposed: ‘The resulting hydraulic conductivity over the length of the borehole shall be lower than $10^{-6}$ m$^{-1}$’;

- for lower strength sedimentary host rocks, where hydraulic conductivities in the range $10^{-10}$ to $10^{-13}$ m$^{-1}$ s$^{-1}$ are typical, radionuclide transport through the host rocks to a sealed borehole is diffusion-controlled; in these circumstances, even poorly sealed site investigation boreholes (modelled by ANDRA as having hydraulic conductivity of $10^{-6}$ m$^{-1}$ s$^{-1}$) do not significantly affect radionuclide flux out of the geosphere;

- for evaporites, where hydraulic conductivities in the range $10^{-10}$ to $10^{-14}$ m$^{-1}$ s$^{-1}$ are typical for halite, US DoE assert that groundwater flows at WIPP associated with historical, current, near-future and future boreholes that do not intersect the waste disposal region can be eliminated from PA calculations on the basis of low consequence to the performance of the disposal system. The German salt programme does not consider sealing boreholes explicitly, but the reference safety assumption is that long-term creep of the host rock will ensure that all underground openings will eventually close, thus restoring the original barriers.

4.4 Numerical modelling of the impact of site investigation boreholes on groundwater flow in HSR

4.4.1 Approach

The objective of the modelling study [3] undertaken as part of the Phase 2 borehole sealing project was to determine the potential impact of a site investigation borehole (either open or sealed) on steady-state groundwater flux and path lines in two illustrative HSR environments; one in which HSR extends to ground surface and one in which the HSR host rock is overlain by sedimentary rocks containing lower permeability formations. Such an approach has already been used on behalf of SKB [24] and Posiva [26] to demonstrate the impact of site investigation
boreholes at sites being investigated for their suitability to host a GDF; see Chapter 6 of the Year 1 Annual Report [2] for a summary.

Impacts on groundwater flow rate and path lines statistics were determined at three different length scales around the borehole, from the kilometre scale to the sub-metre scale. The metric used to evaluate the effect of the borehole was the extent of the difference in the calculated parameter in the presence and absence of the site investigation borehole.

4.4.2 The models

Numerical models of HSR environments were developed in Amec Foster Wheeler’s ConnectFlow modelling software [27], and were based on the geological descriptions, cross-sections and parameter values given in [19]. The volume modelled for the case where HSR extends to ground surface was 10 km long by 2 km wide by 1.2 km thick. In the case where the HSR host rock is overlain by sedimentary rocks containing lower permeability formations, the length of the modelled volume was greater (94 km), because of the larger expected horizontal dimension of the groundwater pathway from the GDF.

The calculated steady-state groundwater flows in these models (see [3] for details) will be illustrative of the types of flows expected in the generic geological environments modelled. The models were not calibrated in any way based on an understanding of groundwater travel times in such environments, nor were parameters systematically varied to explore, for example, the impact of variable vertical pressure gradients on groundwater flow though a sealed or open borehole. The focus was on a comparison of groundwater flow in the presence or absence of the site investigation borehole, rather than on the development of numerical models that represent the characteristics and uncertainties of the generic geological environments of potential relevance to RWM.

Previous site-specific groundwater modelling of the effects of open or poorly sealed site investigation boreholes in HSR environments has shown the importance of borehole location relative to the potential GDF and to transmissive fracture zones. The simulated site investigation boreholes therefore penetrated both the Target Rock Volume, the volume of rock being investigated for construction of the GDF, and fracture zones within the HSR. See Table 4-1 for details.

4.4.3 Conclusions

The results of the modelling highlighted that the impact of a site investigation borehole will depend on both the properties of the host rock and on the overall geological and hydrogeological environment. Notwithstanding this, it was shown that even poorly sealed boreholes (as represented by the granular seal case) do not significantly affect large-scale (km scale) or medium-scale (100m scale) groundwater flow patterns around the borehole in the illustrative HSR environments considered.

Figure 4-1 shows groundwater flow paths in the illustrative environment where HSR extends to ground surface in (i) the absence of the site investigation borehole and (in ii to iv) the presence of a site investigation borehole sealed in different ways. In these simulations, particles for the path line calculations are released at GDF depth in the local area (100m by 100m) around the borehole, which is shown as the black line. Forward path lines are shown in blue; backward path lines in red. The volume shown is the whole computational domain (10 km long by 2 km wide by 1.2 km thick). Only in the case of an open borehole (represented by the ‘no seal’ cases in Figure 4-1 and Figure 4-2) can a slight change in some path lines be seen. Figure 4-2 shows the case in which particles are released at GDF depth within 0.2m of the borehole; here, the impact of the borehole on forward pathlines (shown in blue) can be see for both the borehole sealed with granular material and the open borehole. Note that only in the latter case does groundwater flow along the borehole from GDF depth to the near surface.

The modelling has enabled an improved understanding of the length scales over which site investigation boreholes can perturb groundwater flow and of the impact of different sealing approaches on these impacts. It was recognised in [3] that the modelling approach does not equate to a direct assessment of the impact of the site investigation borehole on ‘geosphere
containment’. However, it is a precursor to such a calculation, and is all that is possible at this generic stage of RWM’s programme, before a site or disposal concept have been chosen.

Figure 4-1  Groundwater flow paths in an illustrative HSR environment in (i) the absence of the site investigation borehole and in (ii to iv) the presence of a site investigation borehole sealed to different standards. Particles for the path line calculations are released at GDF depth in the local area (within 100m) around the borehole, which is shown as the black line. Forward path lines are shown in blue; backward path lines in red.)
Figure 4-2  Groundwater flow paths in an illustrative HSR environment in (i) the absence of the site investigation borehole and in (ii to iv) the presence of a site investigation borehole sealed to different standards. Particles for the path line calculations are released at GDF depth in the immediate area (within 0.2m) around the borehole, which is shown as the black line. Forward path lines are shown in blue; backward path lines in red.
4.5 Summary of understanding gained from approaches

Three approaches to build understanding of the required standard of borehole sealing have been presented: simple analytical modelling to illustrate the relative importance of different pathways; review of site-specific modelling undertaken by other WMOs (ANDRA, US DoE, SKB, Posiva and NWMO [2]), and; comparative groundwater flow modelling using numerical models. A combination of these three approaches is sufficiently robust to confirm that, from a performance assessment perspective, borehole seals in HSR need not have a permeability as low as that of the HSR itself. This is an important conclusion, because it means that a range of borehole sealing concepts are potentially acceptable and can be considered in the Phase 2 programme.

The project did not undertake numerical modelling of LSSR or evaporite (‘halite’) host rocks because simple arguments based on RWM’s definitions of these host rocks are sufficient to demonstrate that groundwater flow through these rocks will be negligible or non-existent. Site-specific modelling of boreholes in LSSR and halite at localities in countries outside the UK confirms that sealed boreholes can have hydraulic conductivities of up to 10^{-5} or 10^{-6} m s^{-1} without significantly affecting radionuclide flux out of the geosphere.

Notwithstanding the relatively high permeabilities for sealed boreholes that might be acceptable from an ESC perspective, experimental results from this project (presented in Section 7.4) show that the standard of borehole sealing that can be achieved using bentonite pellets or blocks is likely to be significantly higher than required by the ESC. The laboratory experiments undertaken as part of this project show calculated hydraulic conductivities of less than 10^{-6} m s^{-1} with seals formed from bentonite pellets, and of less than 10^{-11} m s^{-1} with seals formed from bentonite blocks. These hydraulic conductivity values are very much lower than acceptable hydraulic conductivities for sealed boreholes in a range of geological environments. This indicates that borehole seals formed from bentonite are expected to yield hydraulic conductivities that are suitable for the purposes of borehole sealing.

From a GDF performance assessment perspective, borehole seals in HSR need not have a permeability as low as that of the HSR itself.

Site-specific modelling of boreholes in LSSR and halite at sites outside the UK confirms that sealed boreholes can have hydraulic conductivities of up to 10^{-5} or 10^{-6} m s^{-1} without significantly affecting radionuclide flux out of the geosphere.

Experimental results from this project are presented in Section 7.4 and show that the standard of borehole sealing that can be achieved using bentonite pellets or blocks is likely to be significantly higher than required by the ESC.

4.6 Numerical modelling to optimise the arrangement of components of the borehole sealing system

The arrangement of seals and supports in a borehole at the site of a potential GDF will need to be optimised to:

- ensure the required GDF performance is achieved under the site-specific conditions;
- ensure that groundwater resources are protected from other threats such as naturally occurring saline water bodies and surface-derived anthropogenic contamination, and;
- consider cost appropriately, for example by simplifying the sequence of operations required to install the borehole sealing system, subject to ensuring performance and addressing stakeholder concerns.
The first two items listed above are regulatory requirements.

It is likely that the optimisation process will conclude that borehole seals will not be required over the full thickness of lower permeability rocks penetrated by the borehole. Support elements would entirely fill remaining sections of the borehole, with the exception of any locations occupied by bridge plugs. This would include any sections of borehole that penetrate higher permeability sections of rock, either within the GDF host rock or in the overlying sedimentary rocks.

The numerical model and modelling approach described in subsection 4.4 have been used to illustrate the consequences of different combinations of borehole seals and supports on groundwater flow in HSR environments. The results are reported in [8] and summarised below. The model presented in subsection 4.4 represented the site investigation borehole as having the same permeability throughout its length. To explore the consequences of varying the number of borehole seals and the permeability of the support elements, the borehole is now represented by three types of material: the borehole seal; a support element for use at locations where higher transmissivity fracture zones intersect the borehole, and a support element for lower permeability sections of borehole. These components were previously described in subsection 3.3.

A schematic of the arrangement of seals and supports considered in the modelling of the illustrative HSR is given in Figure 4-3, which builds on the arrangement shown in Figure 3-3. Seals (shown in red in Figure 4-3) are placed above and below local and minor fracture zones where they intersect the borehole. They are represented as being 30m long in the model, and their purpose is to isolate the higher transmissivity fracture zones from the borehole and prevent flow along the borehole. To minimise the section of borehole affected by any such flow, which is illustrated in Figure 3-1, the borehole seals are located close to the fracture zones. In the model, the seals are represented with a hydraulic conductivity of $10^{-10}$ m/s, as was the case for such materials in the modelling presented in subsection 4.4.

![Figure 4-3](image_url)

**Figure 4-3** Schematic illustration and details of the borehole sealing system represented in one of the modelling simulations to illustrate optimisation of the borehole sealing system in HSR. Reproduced from [8]
Support elements for higher transmissivity sections of borehole (shown in yellow in Figure 4-3) are placed at the locations of these fracture zones, and provide support to the overlying and underlying seals. As noted in subsection 3.5, they have low permeability at the time of seal emplacement in order to protect the seals from flows in the adjacent fracture zone during emplacement. Low permeability is not required of this support element in the longer term, and the hydraulic conductivity used in the model \(10^{-1} \text{ ms}^{-1}\) is representative of this period. In the model, support elements for lower permeability sections (shown in blue in Figure 4-3) fill the remainder of the borehole; in the model they are represented as a granular material with a hydraulic conductivity of \(10^{-5} \text{ ms}^{-1}\), as was the case for such materials in the modelling presented in subsection 4.4.

The following conclusions were drawn from this modelling study.

Sealing higher transmissivity fracture zones that intersect the borehole close to GDF depth has greater impact (in terms of minimising any increase in groundwater flux through the rock at GDF depth) than sealing higher transmissivity fracture zones that intersect the borehole at shallower depth. The benefit, in the context of post-closure performance assessment, of sealing higher transmissivity fracture zones that intersect the borehole at shallower depth may be limited.

In some borehole sealing strategies, support elements could fill a significant part of the borehole. If these support elements are formed from highly permeable materials such as coarse gravel, this could affect the capture zone of the borehole at GDF depth and the perturbation of groundwater path lines arising from GDF depth. This would occur if path lines from GDF depth enter the borehole at elevations where support elements are present or if borehole seals can be “by-passed” by flow through the adjacent rock mass. These are particular issues for HSR, where flow is heterogeneous. Longer borehole seals and the use of lower permeability support elements would remove the problem.

The modelling results in Figure 4-4 demonstrate that, in the system being modelled, a support element with hydraulic conductivity of \(1 \times 10^{-5} \text{ ms}^{-1}\), typical of a silty sand, would not significantly perturb groundwater path lines arising from GDF depth in an environment where HSR extends to the ground surface. This is consistent with the results presented previously in the ‘granular material’ case in Figure 4-2.

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10 The proportion of pathlines from GDF depth that enter the borehole between fracture zones would depend on the contrast in permeability between the fracture zone and the rock between fracture zones and on the spacings, thicknesses and connectivity of the fracture zones. In the bounding case where no flow occurs through the rock between fracture zones, hydraulic conductivity of the support material would have no impact on groundwater pathlines. In the case where most pathlines from GDF depth enter the borehole between fracture zones, the hydraulic conductivity of the support material has the potential to impact significantly on groundwater pathlines.
Figure 4-4  Forward pathways for particles released within 0.2m of a borehole in HSR (the ‘IRV release’) at elevations -780m, -730m and -680m. The lowest elevation shown in the figures is -780m, the deepest position at which particles are released. The shallowest elevation shown is the elevation at which all released particles have re-entered the rock. Top: only fracture zone L2 is sealed. The remainder of the borehole is filled with support material with hydraulic conductivity of $1 \times 10^{-5}$ ms$^{-1}$. Bottom: the borehole is sealed along its full length with material with hydraulic conductivity of $1 \times 10^{-9}$ ms$^{-1}$. See text for details.
5 Selection of materials for borehole seals and supports

5.1 Introduction

Borehole seals will be required to provide some sealing against groundwater flow on timescales potentially up to 1 Ma. The long-term physical and chemical evolution of borehole seals should therefore be understood, and it will be necessary to demonstrate that any changes will not compromise the performance of the seal on long timescales. Borehole sealing materials that minimise such changes and for which robust arguments about long-term physical and chemical evolution can be made are favourable for this requirement.

When considering the longevity of borehole seals, it is also necessary to consider the movement of the rock around the borehole. The evolution of the BDZ around boreholes in HSR, LSSR and halite was considered in Task 13 of the project [10]. The literature survey presented in that report concluded that:

- in HSR there is little potential for self-sealing of the BDZ or for sealing the void space created by the borehole. However, there are processes that may serve to reduce the aperture of fractures and hence reduce the permeability of the BDZ in the longer term;
- LSSR are capable of self-sealing excavation-incurred damage around boreholes. However, there are expected to be limits to the sealing achieved, dependent on rock type and compressive stress, and healing does not appear to be fully achievable. In particular, it is expected that fractures may reopen if subject to gas overpressure;
- salt (halite) creep will act to anneal fractures in the BDZ. Further, creep will close the void created by the borehole over a timescale of hundreds of years. Gas storage in evaporites is a proven technology that is successfully operated at many locations worldwide, and relies on these sealing properties of rock salt.

In summary, it is unlikely that long-term movement of HSR around a borehole would contribute to sealing the borehole against groundwater or gas flow. In LSSR, creep and self-sealing processes are considered likely to contribute towards borehole sealing against groundwater flow in the longer term by counteracting some of the effects of seal degradation, for example by sealing any annular gap created by seal shrinkage and by applying a confining stress on the seal. However, complete sealing of void spaces may not be achievable. In contrast, there is high confidence that creep processes in halite would seal void space created by the borehole on a relatively short timescale (hundreds of years).

Given the above, we recommend that borehole seals in HSR and LSSR should be formed from ‘natural’ materials that are expected to be stable in the hydrogeochemical environment of the rocks through which the borehole is drilled. Examples of candidate natural materials that are unlikely to undergo significant interaction with naturally occurring groundwaters over timescales of relevance to performance assessment include bentonite, crushed rock and graded silica. It would not be appropriate to form borehole seals from ‘engineered’ materials such as Ordinary Portland Cement (OPC), which would undergo significantly greater chemical interactions with the surrounding rocks and groundwater and which could physically and chemical degrade over a timescale of 1 Ma with potential substantial increase in hydraulic conductivity.

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11 We recognise that many of these ‘natural’ materials have undergone some form of processing, such as size grading for granular materials like crushed rock and graded silica or drying, milling and possible sodium activation in the case of bentonite. However, we take the view that this level of processing falls short of the processing required to form ‘engineered’ materials such as OPC, and therefore distinguish these two categories of materials.
Borehole seals in evaporites (halite) could be formed from either natural or engineered materials, because the long-term creep of the rock around the borehole will aid sealing in the long term. That said, the long-term performance of seals formed from natural materials would be easier to demonstrate. A combination of naturally occurring materials and appropriate cementitious formulations may be necessary because only the latter will provide low permeability in the short term (see Section 9 for further discussion).

Borehole support elements are required to provide mechanical support and confinement for seals for as long as required by the environmental safety case. Any longer-term consolidation/settlement of the support element that results from physical rearrangement of grains in the material, from chemical degradation or from erosion should not compromise this requirement (see [9] for further discussion). For example, materials selected for use as supports in higher transmissivity and permeability sections of borehole must be chosen taking account of the stability of the support against erosion. Support elements should also be chosen so that any chemical interactions with adjacent seals must not compromise the performance of the seal on long timescales. A range of natural and engineered materials exhibit the required properties for support elements and therefore would be suitable candidate materials for support elements.

5.2 Borehole seals

5.2.1 Selection of materials for borehole seals

The required properties of borehole seals and the approach to selecting appropriate materials are discussed in subsection 3.5. A more detailed description is given in subsection 9.4 of [2]. The attributes for candidate materials that were considered in [2] were:

- hydraulic conductivity at emplacement. Hydraulic conductivities on emplacement in a perfect cylindrical borehole and in a borehole with significant variability in diameter ('rugosity') were both considered;
- longevity. This included resistance to chemical degradation and resistance to erosion;
- issues during emplacement The issues considered included loss of material by erosion during emplacement and potential segregation during emplacement, which could lead to a seal with heterogeneous properties;
- proven technique. This considered the previous use of the material as a sealing element. For example, is it standard practice? Tested on a small scale in the laboratory? Untested?
- simplicity of concept. The simpler the concept, the easier it will be to successfully emplace the borehole sealing system and to demonstrate it had been placed in accordance with the design.

A number of materials that could potentially be used to form borehole seals in HSR and LSSR, and some of their relevant characteristics were considered in subsection 9.4 of [2]. These materials were grouped into three categories, which were also used in a subsequent study [4] to identify techniques that would be potentially suitable for placing materials in boreholes:

- high density sealing elements;
  - bentonite blocks;
- granular materials:
  - bentonite pellets;
  - sand/bentonite;
  - graded sand/crushed rock;
pumpable materials:
- graded silica\textsuperscript{12};
- cement (OPC or low-alkali formulations);
- soil/bentonite slurry;
- sand bentonite slurry mixtures;
- cement/bentonite slurry.

The characteristics of these materials were summarised in Table 9.1 of [2], and the following conclusions drawn:

- cement is often used as a borehole seal in the hydrocarbon industry. However, because of the requirements on longevity it is unlikely to be suitable as a borehole seal in the context of a GDF site, although it is likely to function well as a support element;
- cement/bentonite slurry was considered to be unsuitable for use as a borehole seal because of concerns about longevity, as a result of interactions between the cement and bentonite components;
- concerns with potential segregation during placement were identified for mixtures of materials.

The potential suitability of the above materials for forming borehole seals in HSR and LSSR was reviewed and it was considered that the following would be ‘highly suitable’ in at least one situation, such as boreholes with uniform diameter and boreholes with highly variable diameter:
- high density sealing elements: bentonite blocks;
- granular materials: bentonite pellets, sand/bentonite and graded sand/crushed rock;
- pumpable materials: graded silica and sand/bentonite slurry mixtures.

Of these materials, bentonite pellets and granular sand/bentonite mixtures were considered to have the widest application. We subsequently concluded [9] that materials such as sand/bentonite, crushed rock and graded silica, which were identified in [2] as being potentially suitable as either a seal or a support element, should be considered only as potential support elements.

The result of this process is that bentonite was identified as the preferred material for forming borehole seals in HSR and LSSR. The properties of bentonite that are relevant to its use in borehole seals are described in subsections 5.2.2 to 5.2.4. Subsection 5.2.2 describes the general characteristics of bentonite (see [12] for further information). The relationships between dry density, water composition and hydraulic conductivity of bentonite are described in subsections 5.2.3 and 5.2.4.

It was concluded previously that borehole seals in evaporites could be formed either from appropriate cementitious materials or from natural evaporite minerals.

\textsuperscript{12} The review in [1] and [2] identified only a single example of this kind of material, Sandaband\textsuperscript{TM}, a proprietary material produced by Sandaband Well Plugging AS, a company based in Stavanger, Norway. Further information is provided in [9].
5.2.2 General characteristics of bentonite

Chemical composition
The term ‘bentonite’ was first applied in 1898 to highly colloidal, plastic clay in Cretaceous beds of Wyoming. The term was redefined as clays produced by the in situ alteration of volcanic ash to produce mainly smectite, but has been used more recently to refer to smectite-rich material regardless of its origin. It is this last definition that has been widely adopted by WMOs, and is used within the Sealing of deep site investigation boreholes project. The bentonite that is typically specified in radioactive waste disposal concepts consists primarily of montmorillonite (a smectite group clay mineral), with interlayer calcium or sodium and minor amounts of quartz, feldspar, kaolinite, carbonates, sulphides, sulphaes and organic matter.

Smectites are ‘2:1 layer’ clay minerals, in which a tetrahedral sheet is ‘sandwiched’ between two octahedral sheets (Figure 5-1). The dioctahedral aluminous smectite minerals typically present in bentonite are represented by the montmorillonite-beidellite series according to the formula \((\text{Al}_{2-y}\text{Mg}_y^{2+})\text{Si}_{4-x}\text{Al}_x\text{O}_{10}(\text{OH})_2\text{E}^{m+}_{(x+y)/m}\text{nH}_2\text{O}\), where \(\text{E}^{m+}\) represents the interlayer cation neutralizing the negative layer charge, \(x\) and \(y\) are the octahedral and tetrahedral substitutions respectively. For smectites \(x+y\) ranges from 0.2 to 0.6 by definition. Smectite with \(y > x\) are referred to as montmorillonite, and that with \(y < x\) are referred to as beidellite. In this report, we are concerned with the properties of montmorillonite, a dioctahedral smectite group mineral that is characterized as having greater than 50% octahedral charge; its cation exchange capacity is due to isomorphous substitution of Mg for Al in the central alumina plane.

Borehole seals in HSR and LSSR should be formed from bentonite.

Borehole seals in evaporite could be formed from either natural evaporite minerals or from appropriate cementitious materials such as salt cement or Sorel cement. Only cementitious materials will provide low permeability in the short term, before convergence by creep of the surrounding halite has occurred.

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Figure 5-1 Simplified ‘ball and stick’ model of an idealised C2/m smectite structure (reproduced from [12])
General cause of swelling pressure

Generally, ions in a water solution reduce the chemical potential of the water, and a concentration difference between different parts of a clay normally leads to water transport from the volume with low ion concentration (high chemical potential of water) to the volume with high ion concentration (low potential). In parallel, ions will diffuse from the high ion concentration to low ion concentration volume, and the equilibrium condition, i.e. equal chemical potentials for both water and ions, respectively, leads to uniform ion concentration in the clay/water solution.

In bentonite, the charge-compensating positive ions cannot freely diffuse away from the negatively charged montmorillonite layers because of the demand for electrical neutrality. Water, on the other hand, can move to the charge-compensating ions, and the distance between the montmorillonite layers will thereby increase, which is synonymous with swelling. Such water uptake will continue until the chemical potential is equal, which in the case of a pure water source and monovalent charge compensating ions theoretically leads to infinite swelling [28]. The extent of water uptake in bentonite may thereby be orders of magnitude larger than in other clay materials that are not rich in swelling phyllosilicates.

A special case of bentonite swelling is when the space is limited for the bentonite-water system, and the contact with water is through a semi-permeable membrane, which lets water through but not bentonite. The membrane may be a filter in a laboratory experiment or a fine fracture or pore in a rock. These conditions induce swelling until the total available pore volume is completely filled with water and the chemical potential of water in the system is equalized by the build-up of a swelling pressure.

Swelling pressure is consequently only defined in relation to a reference water solution, and the simplest reference case is pure water. Equilibrium with saline solutions means different chemical potential not only in the reference solution, but also in the bentonite because of the introduction of ions into the montmorillonite interlayers [29]. Cations typically found in the interlayer regions are sodium, calcium, magnesium and potassium; others can be introduced deliberately in the laboratory by the repeated reaction of smectite with concentrated salt solutions containing the desired interlayer ion.

5.2.3 Relationship between the dry density and hydraulic conductivity of bentonite

Bentonite is an important component of the EBS in several international repository concepts. The relationships between the initial dry density of the bentonite and the final saturated swelling pressure and hydraulic conductivity are therefore well established, as shown in Figure 5-2 which is reproduced from subsection 9.5 of [2]. Data in Figure 5-2 show a very strong dependency between hydraulic conductivity and dry density that can be approximated by a linear relationship in a semi-logarithmic diagram in the bentonite density range between 500 kg/m³ and 1,700 kg/m³.

In an ideal cylindrical borehole with constant diameter, the maximum as-placed density (and hence lowest hydraulic conductivity) of bentonite can be achieved using cylindrical high density bentonite blocks that are formed to have diameters slightly smaller than that of the borehole. Bentonite blocks with dry density of approximately 1,900 kg/m³ can be manufactured from MX-80 bentonite, and were used in the experimental programme for the current project [5, 6].

The dry density of individual MX-80 bentonite pellets varies depending on the manufacturing method (see Sections 2 and 3 of [5]), but can be as high as that of high density bentonite blocks (i.e. approximately 1,900 kg/m³). However, the dry density (or ‘placed density’) of the bulk material is substantially lower because of the voids between the pellets. For the uniform-sized MX-80 bentonite pellets used in the laboratory programme undertaken as part of the Phase 2 borehole sealing project, dry bulk densities were between 880 kg/m³ and 970 kg/m³. The measured dry densities of the uniform-sized MX-80 bentonite pellets after installation in simulated water-filled boreholes ranged between 840 kg/m³ and 880 kg/m³ [5, 6]. A summary of the laboratory programme undertaken as part of the sealing boreholes project is given in Section 7.
The project recognises that higher as-placed densities of bentonite pellets could potentially be achieved by:

- using spherical pellets rather than the ‘pillow-’ or ‘almond’-shaped bentonite pellets used in the Stage 1 and 2 laboratory programmes. An increase in as-placed density would arise from the improved packing geometry of spherical pellets. However, to achieve this benefit, it would be necessary for the spherical pellets to have the same or higher particle densities as the ‘pillow-’ or ‘almond’-shaped bentonite pellets used in the laboratory programme. As noted in subsection 2.1 of [5], it is not clear that this could be achieved;

- using pellets with a range of particle sizes, rather than the uniform particle size used in the Stage 1 and 2 laboratory programmes. The use of bimodal or graded particles could increase as-placed density through improved packing geometry. For example, Table 9.1 of [2] reports in-situ dry density of up to 1,450 kg/m³ for a bentonite backfill formed from a mixture of particle sizes. However, using bimodal or graded particles could result in physical separation caused by differing settlement speeds if the particles are dropped into a water column (e.g. a water-filled borehole). This would negate the benefit of using pellets with a range of particle sizes, and could even be detrimental.

Note that, as described in subsection 6.4, it might be possible to further compact bentonite pellets after emplacement in the borehole through the use of a dump bailer employed on modified core drilling equipment. At present, this system is at the conceptual design stage.
Finally, the maximum density of a bentonite slurry (containing either saturated bentonite or fine pellets of unsaturated bentonite; see [4] for further discussion) will be controlled by its rheological properties; the requirement is that the slurry must be pumpable. The maximum density of the slurry will depend on the distance over which it is to be pumped, on the water composition in contact with the slurry and on the capacity of the pumps used to place the bentonite. In general, the density of the slurry would be substantially lower than that of bentonite pellets. To increase the potential application of bentonite slurries for borehole sealing, the project has investigated the relationship between water chemistry and the rheological properties of the slurry (to maximize the pumpable density) and concluded that a dry density of up to about 730 kg/m$^3$ is practicable [5].

Equation 1 below, reproduced from subsection 4.4 of [12], shows the relationship between the radius of a cylindrical bentonite block and the homogenized placed density of the bentonite as a function of the radius of the borehole and the dry density of the block.

$$T_d = T_h \left( \frac{\rho_{dh}}{\rho_{db}} \right)$$

(1)

where

- $r_b$ = block radius (m)
- $r_h$ = hole radius (m)
- $\rho_{dh}$ = average dry density in the borehole (kg/m$^3$)
- $\rho_{db}$ = average dry density of the blocks (kg/m$^3$)

For example, if the placed dry density of bentonite pellets was assumed to be 1,000 kg/m$^3$ in a cylindrical borehole of constant radius 83 mm (0.083m), and the dry density of the bentonite block was 1,900 kg/m$^3$, then Equation (1) demonstrates that the placed density of bentonite using the block approach would be greater than that of the pellets as long as the radius of the block was greater than 60 mm (0.060m); that is, an annular gap of width 23 mm (0.023m). This width is substantially greater than needed to place the block (see subsection 3.4.2 of [4], which concludes that an annular gap of 1.5 mm (0.0015m) would be sufficient in an ideal borehole), demonstrating the advantage of placing bentonite blocks in boreholes with small or no variability in diameter.

Equation (1) can be rearranged to determine the degree of borehole enlargement at which the as-placed density of bentonite pellets would be equal to that of a cylindrical bentonite block$^{13}$. The radius of the bentonite block is assumed to be 81 mm (0.081m)$^{14}$; the radius of the in-gauge section of borehole is assumed to be 83 mm (0.083m). In this case, the as-placed densities of

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$^{13}$ This assumes that the pellets can flow out to completely fill the section of enlarged borehole, and that the bentonite in the block can become homogenised in the borehole through radial swelling (i.e. no expansion along the borehole axis); assumptions regarding pellet filing and homogenisation are investigated further in subsections 7.2.1 and 8.3.

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$^{14}$ This is the maximum possible radius, and assumes the bentonite is placed using a ‘couronne arrangement’. See Figure 4.2 of [1] for a schematic. Section 4 of this report recommends using a dump bailer to place bentonite blocks in boreholes of radius 80 mm or greater; in these circumstances, the diameter of the block would be reduced because of the wall thickness of the bailer and the need for a gap between the block and the inner surface of the bailer.
the block and pellets would be equal if the radius of the enlarged section of borehole is 112 mm (0.112m). Although this is greater than the average modal enlargement of 20% calculated in LSSR using borehole stability analysis (subsection 2.7), it is substantially less than the observed breakout in Figure 4.2 of [7], where enlargements greater than 0.5m are evident in a 0.1m nominal borehole.

Once the actual characteristics of the borehole have been determined and the emplacement techniques identified, it will be possible to use the approach described above to determine which form of bentonite would give the highest as-placed density. Note, from the illustrative discussion above, that the use of high density blocks could still be preferred even if the as-placed density was a factor of two times lower than that of the actual block itself. The data in Figure 5-2 indicate that this reduction in density would lead to an increase in hydraulic conductivity of more than a factor of ten. The experimental results reproduced in Figure 5-2 show that bentonite with a dry density of approximately 500 kg/m$^3$ would have a hydraulic conductivity of less than $10^{-9}$ m$^2$s$^{-1}$ in NaCl solutions up to 3M. Under these circumstances, bentonite formed from any of blocks, pellets or slurry would be suitable to achieve the design requirement of $10^{-9}$ m$^2$s$^{-1}$ or $10^{-6}$ m$^2$s$^{-1}$ discussed in subsection 4.5.

5.2.4 Relationship between water chemistry and hydraulic conductivity of bentonite

An important aspect of bentonite is that the swelling behaviour is strongly influenced by the composition of the water in contact with the bentonite. If the bentonite is physically confined, as would be the case for a borehole seal, the bentonite will exert a swelling pressure as it saturates. At full saturation, the equilibrium swelling pressure is controlled by the initial dry density of the bentonite, the proportion of montmorillonite in the bentonite and the water composition. In turn, the hydraulic conductivity of the bentonite at saturation is controlled by the swelling pressure; hydraulic conductivity decreases as swelling pressure increases.

The relationship between hydraulic conductivity of bentonite and water composition is well understood. For example, Figure 5-2 shows that:

- hydraulic conductivity of Na-saturated MX-80 increases as the Na concentration increases. The effect is most pronounced at lower dry densities. For example, the hydraulic conductivity of Na-saturated bentonite with a dry density of approximately 500 kg/m$^3$ increases by approximately two orders of magnitude as Na concentration is raised from 0.1M to 3M;
- hydraulic conductivity of Na-saturated MX-80 with dry density of 800 kg/m$^3$ is more than two orders of magnitude higher than that of the equivalent Ca-saturated bentonite;
- the difference in hydraulic conductivity of Na-saturated and Ca-saturated forms of bentonite is much less at higher dry densities.

At the current generic stage of the UK GDF siting programme, the range in groundwater compositions that could be encountered by deep site investigation boreholes is large, as shown
in Table 2-2. An understanding of the relationships between the initial density of the bentonite, the composition of the water in contact with the bentonite and the hydraulic conductivity of the bentonite after saturation will be required to determine the minimum density of bentonite necessary to achieve the required hydraulic conductivity in contact with a particular groundwater composition.

Control of the water composition during seal emplacement could be beneficial for some sealing concepts, for example to maximise the pumpability of a slurry or to reduce the total amount of swelling during emplacement. This could be achieved by replacing the water in the open borehole (only possible in low permeability environments) or by controlling the water composition in a tremmie pipe or dump bailer used to place the bentonite.

However, in the longer term, the swelling pressure and hydraulic conductivity of the bentonite will be controlled by the composition of the natural groundwater in contact with the seal. If solute transport through the bentonite is assumed to be diffusion-dominated (this will maximise the time for equilibration with the groundwater), scoping calculations in subsection 6.2 of [1] indicated that, for the case of radial diffusion geometry, the bentonite could approach cation exchange equilibrium across the entire width of the seal after about 50 years.

The impact of groundwater composition on seal properties should be determined for the range of groundwater compositions of potential relevance in HSR and LSSR environments.

5.3 Support elements

5.3.1 Candidate materials for support elements

Support elements will be used to fill those sections of borehole where seals are not placed. They could therefore be placed in sections of the GDF host rock and in any overlying sedimentary rocks (in environments where there is sedimentary cover above the host rock) or underlying rocks. The permeability of the section of borehole in which the support element is to be placed is likely to significantly influence the choice of material for the support element. The principal reason is that, for some materials, there may be an upper limit on the groundwater flux or velocity past the support element. We therefore sub-divide the possible locations for borehole support elements into ‘higher permeability’ and ‘lower permeability’ sections of borehole.

- Support elements in the GDF host rock:
  - support element is placed across a higher permeability section of the host rock, where it is inappropriate to place a seal: a higher transmissivity fracture zone in HSR or a higher permeability interbed (such as a sandstone horizon) in LSSR. The rationale for not placing seals across more permeable zones in a borehole is that the preferred material for the seal (bentonite) is susceptible to erosion. This is discussed further in subsection 8.2. A support element located across a higher permeability section of the host rock is likely to be short; if high permeability zones were of substantial thickness, the rock is unlikely to be suitable as a host rock for a GDF. The number of support elements in the GDF host rock would depend on the number of higher transmissivity fracture zones or higher permeability interbeds intersecting the borehole;
  - support element is placed across a lower permeability section of the host rock. This would occur if it was decided that the full length of the GDF host rock intersecting the borehole did not require sealing. Optimisation of the configuration of seals and support elements was considered in subsection 4.6. If used, the length of such support elements would depend on the overall thickness of the GDF host rock and on the required length of the borehole seals;
Support elements in sedimentary rocks overlying the GDF host rock or in underlying rocks:

- support element is placed across a higher permeability section of borehole. Higher permeability sections of borehole will likely correspond with rock type; groundwater flow in such rocks may be through fractures or the rock matrix, or through a combination of the two. In addition, higher permeability may occur where the borehole is intersected by larger-scale fracture zones. The length and number of support elements would depend on the nature of the rocks and by the presence of tectonic features such as fracture zones;

- support element is placed across a lower permeability section of borehole. Lower permeability sections of borehole will correspond with rock type. The length and number of support elements would depend on the nature of the rocks.

The main required attributes \[9\] are that the materials for support elements should be resistant to:

- loss of material by erosion that is sufficient to significantly impair the confinement / support provided to the adjacent seals. This attribute is only relevant for support elements placed in higher permeability sections of borehole;
- chemical degradation that results in a volume loss sufficient to impair the confinement / support provided to the adjacent seals;
- grain realignment/settling following emplacement that results in a volume loss sufficient to impair the confinement / support provided to the adjacent seals;
- chemical interactions with adjacent post-closure seals, such that the performance of the post-closure seal is compromised on longer timescales.

In addition:

- support elements placed across higher transmissivity features will need to have a low permeability when placed, in order to protect the adjacent seal from flows within the borehole during emplacement. Cementitious materials would be suitable for this purpose;
- EA guidance on borehole sealing \[31\] requires boreholes to be decommissioned in a manner that protects groundwater resources from ingress of saline water or surface-derived contamination. The key issue regarding this guidance is that the timescale over which such protection is required will be much less than that required in the ESC for a GDF. Protection of groundwater resources could be achieved by placing seals at appropriate locations within uncased sections of borehole (most likely within lower permeability cover rocks) or by ensuring that support elements within uncased sections of borehole have suitably low permeability.

Section 5.1 of this report recommended that borehole seals should be formed from bentonite (a ‘natural’ material) because ‘engineered’ materials such as OPC cannot be guaranteed to retain low permeability in the long term. Engineered materials are, however, potentially acceptable for forming support elements. When deciding whether or not to use an engineered material as a support element in a particular borehole sealing system, it will be necessary to demonstrate that leaching and other reactions with surrounding materials do not affect the support element to the extent that it can no longer provide support or confinement. In addition, it will need to be demonstrated that any chemical reactions between the engineered material and the bentonite do not impair the sealing properties of the latter.

The characteristics and selection of materials for support elements in HSR and LSSR is discussed in \[9\]. Three groups of materials are identified that could potentially meet the requirements that were described in subsection 5.1. Each of these groups spans a wide range of material properties:

- cementitious materials: cement with or without aggregate;
- granular materials:
  - crushed rock;
- crushed rock-bentonite mixtures;
- bentonite-quartz mixtures, and;
- graded silica\(^{15}\), and;

barite-based materials.

Geochemical interactions between cement and bentonite are discussed in subsection 5.3 of [12]. Available information indicates that the extent of the alteration zone between cements and clay-based materials will be spatially limited. Reactive transport models suggest that alteration may be restricted to a scale of centimetres to a few tens of centimetres, with an associated porosity decrease occurring over tens of thousands of years. There could be decrease in the swelling capacity of the bentonite in this zone, leading to a local increase in hydraulic conductivity. However, if the length of the bentonite seal is long compared with this zone (which is almost certain to be the case) then the overall effect on the performance of the seal will be small.

5.3.2 **Approach to selecting the most appropriate material for a support element**

To identify the most appropriate materials for forming support elements in the three environments identified in subsection 3.3 (i.e. high transmissivity features and higher and lower permeability sections of borehole) it will be important to determine:

- the presence of transmissive features (fractures zones) or permeable zones (e.g. sandstone horizons) within an otherwise low-permeability rock;
- if there is any upper limit on the permeability of a borehole section before the suitability of a candidate material for a support element is called into question. For example, there is likely to be a limit on groundwater flux and velocity past the support element above which fine-grained unconsolidated materials might be eroded; and
- if there are any implications of the permeability distribution within a borehole for the performance of a candidate support element material. Relevant aspects are whether all the flow in a section of borehole is focused at one location (see points above) and the contrast in transmissivity between higher and lower permeability sections of borehole.

An approach is proposed in [9] for selecting the most appropriate support element material for use in these different environments in an actual borehole sealing system. The approach has two steps:

- screening each of the candidate materials identified in subsection 5.3.1 against performance criteria that must be met;
- ranking the candidate materials that pass the screening exercise. It should be noted that there are uncertainties about the long-term performance of the various candidate materials, which may have a bearing on the ranking of materials.

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\(^{15}\) Graded silica that is formulated to behave as a Bingham Plastic may be suitable in high permeability sections of borehole, but further Research, Development and Demonstration (RDD) would be needed to demonstrate the conditions, if any, when it could be used.
When the screening scheme in Figure 5-3 is applied, it is concluded that it ought to be feasible to produce at least one example of each group of materials that would fulfil the required performance criteria in lower permeability rock sections. In higher permeability rock intervals, it is concluded that barite-based materials (excluding barite-bearing cementitious materials), bentonite-quartz mixtures and graded silica\(^\text{16}\) would not be suitable. The reason is that these materials are both fine grained and unconsolidated (un-cemented) such that erosion would be a problem.

![Figure 5-3 Relationships among statements corresponding to performance criteria that must be met by a candidate support element material](image)

The proposed approach to ranking support materials for use in higher and lower permeability rock intervals is illustrated in [9] using an example based on one of the generic geological environments referred to in RWM’s gDSSC; HSR extending to the ground surface. In this illustrative ranking exercise, cement and graded silica were the most favoured materials for use

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\(^{16}\) Conceivably uncemented graded silica that is formulated to behave as a Bingham plastic could be used as a support element in higher permeability rock, even when the maximum grain size of the graded silica is smaller than the fracture apertures in the rock. In such a case, when a driving force is removed, the graded silica becomes an impermeable solid (see Appendix C of [9]). When the graded silica enters a permeable rock interval from a borehole, the effective driving force decreases rapidly with increasing distance from the borehole, thereby causing the graded silica to plug the permeable section.
in lower permeability sections of rock; cement was the most favoured material for use in higher permeability sections of rock.

It was also concluded that it would not be possible to definitively rank the candidate materials for support elements at the present, generic, stage of RWM’s GDF siting programme because of the wide range of hydrogeochemical conditions that could be encountered, the range of borehole designs that may be used and the differing strengths and weaknesses of the candidate materials (which might suit one hydrogeochemical environment more than another).

Selection of a support element material can only be undertaken once site-specific and project-specific information is available. Three groups of materials are identified that would fulfil the required performance criteria in lower permeability rock sections. Representatives of two groups of materials are identified that would fulfil the required performance criteria in higher permeability rock sections.

5.3.3 Bridge plugs

Potential requirements for bridge plugs

The potential roles of short deformable plugs (termed ‘bridge plugs’) as part of the borehole sealing system were described in subsection 3.3. These short elements could be used at the upper or lower surfaces of borehole seals, either to provide additional support to the seal or to limit geochemical interaction between the seal and the support element. The actual requirement for bridge plugs as part of a borehole sealing system will depend on:

- whether emplacement of the overlying support element and the subsequent attainment of confining properties occur sufficiently quickly to prevent the bentonite seal swelling up the borehole axis to an extent that the placed density of the seal material reduces below the design requirement;
- whether the spatial extent and nature of the geochemical interaction between the materials used to form seal and support are sufficient to degrade the seal to an extent that it no longer fulfils its required function.

Both these issues are discussed in detail in reference [9]. As noted in subsection 5.3.2 above, it was concluded that geochemical interactions between seals and supports are unlikely to affect the performance of the seal. If there were any concerns about the spatial extent of interactions, this could in most cases be addressed by increasing the length of the seal.

Description of bridge plugs

Bridge plugs are mechanical plugs that are used to seal a borehole, either temporarily or permanently, and typically are around a metre in length. Such plugs are widely used in the hydrocarbon industry to reduce the amount of cement that needs to be emplaced within a borehole abandonment system or to provide additional protection to the well from formation pressures. The bridge plugs used in the oil and gas industry are generally formed from combinations of steel and rubber or nylon. Corrosion is a known issue when using bridge plugs for hydrocarbon well abandonment, and would also be of concern for any bridge plugs used as part of a borehole sealing system at the site of a GDF. Consequently, the Swedish, Finnish and Swiss radioactive waste disposal programmes have all undertaken trials using metallic bridge plugs formed from ductile metals expected to exhibit low corrosion behaviour when exposed to groundwater. Trials with bridge plugs formed from copper and vanadium are described in [7, 9]; a copper plug trialled as part of Posiva’s programme is illustrated in Figure 5-4.
Figure 5-4 A copper “expander” plug. In the photograph a copper plug is turned upside down below the drill rig prior to being lowered into a 200 mm diameter borehole. After emplacement in the borehole on a central rod, the rod is pulled, causing the plug to deform and form a tight seal against the borehole walls. After [32]
6 Techniques for emplacing borehole seals and supports

6.1 Introduction

Task 5 of the Phase 2 borehole sealing project described the techniques used in borehole abandonment in the oil and gas industry, and considered whether and how these techniques could be modified to seal deep boreholes at a site being investigated to host a potential GDF [4]. The project has previously concluded that post-closure seals in site investigation boreholes at a GDF site should be formed from bentonite. Therefore, the Task 6 report specifically considered the application of techniques used in the oil and gas industry to place bentonite-based materials in site investigation boreholes up to 2,000m deep.

6.2 Review of techniques used in the oil and gas industry

Brief descriptions of the main techniques used by the oil and gas industry to place materials in boreholes are given below, together with the types of materials that are currently typically placed using each technique. Further detail is given in Sections 4 to 8 of [4].

- **Conventional pumping.** The use of a combination of drilling rig or ‘workover rig’, tubing string and high power, high rate pump for placing materials in boreholes. This is the default technique for plugging and abandoning oil or gas boreholes internationally, used for most boreholes with few exceptions. The technique is typically used in the oil and gas industry for placing cement-based slurries.

- **Coiled tubing pumping.** The approach has better rate control than conventional pumping, and consequently has developed significantly over the last decades to place small volumes of materials at specific depths. The technique is typically used in the oil and gas industry for placing cement-based slurries and granular materials (sand plugs).

- **Gravity emplacement:** The dropping of the material that will form the seal or support element from surface so that it free-falls inside the borehole intending to land at the bottom of the borehole. The technique is typically used in the oil and gas industry for sealing cased boreholes up to 1,000m deep using bentonite pellets.

- **Dump bailing.** The use of a metallic cylindrical vessel, typically run on wireline, containing a small volume of material that can be released at a desired depth either by gravity alone or by positive displacement. The technique is typically used in the oil and gas industry for placing small volumes of cement-based slurries and granular materials (sand plugs).

- **High velocity and high pressure pumping of particulates.** The emplacement of particulate materials in the borehole or formation by high velocity or high pressure pumping. The techniques are typically used for placing gravel packs, for hydraulic fracturing and for ‘frac-and-pack’, which is essentially a combination of the first two techniques.

Borehole sealing in the oil and gas industry is usually achieved through the use of cementitious materials, although bentonite pellets have been successfully used in recent years to seal near-vertical, generally cased, boreholes up to 1,000m deep. Consequently, with the exception of gravity emplacement of bentonite pellets, the oil and gas industry has no direct experience of placing bentonite for sealing purposes in boreholes, though there is extensive experience of pumping bentonite-based drilling muds for viscosity and filtration control and for blowout prevention.
6.3 Potential application to the emplacement of bentonite

6.3.1 Introduction

After describing each of five techniques for placing materials in boreholes, reference [4] considered the potential application of these techniques for placing bentonite in various forms in site investigation boreholes up to 2,000m deep. The three forms of bentonite considered are slurry, pellets and blocks.

In this part of the Phase 2 borehole sealing project, consideration was given to two types of slurry: ‘liquid slurry’, which would contain very fine-grained bentonite that would be fully saturated before the slurry was pumped into the borehole, and ‘suspension slurries’, which would contain small particles of unsaturated bentonite up to a few millimetres in size. The oil and gas industry has demonstrated the ability to pump fine-grained particulate material into deep boreholes, and the potential application to bentonite was considered as part of the borehole sealing project. The potential advantage would be that densities higher than those in ‘liquid slurries’ could be achieved. However, as emphasised in subsection 3.2 of [4], further research would be needed to determine whether this approach would be feasible.

Table 6-1 summarises this information and the potential for technology transfer in the form of a simple Red – Amber – Green (RAG) ‘traffic light’ system for boreholes up to 1,000m deep. Table 6-2 summarises the same information for boreholes up to 2,000m deep. The RAG classification in Table 6-1 and Table 6-2 is defined for each technique as follows:

- **GREEN.** Routine practice and proven technology in the oil and gas industry for emplacement of a form of bentonite (slurry, pellet, block) in boreholes;
- **AMBER.** Routinely used in the oil and gas industry for emplacement of other materials such as cement, sand and ceramic particles. In our judgment, these techniques could be adapted to place a form of bentonite (slurry, pellet, block) in boreholes at a site of a potential GDF;
- **RED.** In our judgment, the technique is not applicable, or not recommended, for the emplacement of a form of bentonite (slurry, pellet, block) in boreholes at a potential GDF site.

Techniques categorised as **GREEN** and **AMBER** should be considered for application for sealing boreholes at a potential GDF site. Just because the technique is categorised **GREEN** does not mean that it would necessarily be the best approach for sealing site characterisation boreholes. Indeed, as described in Section 6.3.2, we believe that dump bailing is preferable to gravity emplacement. Note that Table 6-1 and Table 6-2 do not consider whether the placed bentonite possesses suitable properties (for example permeability) for the specific seal application. They are only concerned with approaches to place bentonite in site investigation boreholes at a potential GDF site.

In summary, the oil and gas approach to gravity emplacement of bentonite pellets is categorised as **GREEN** for boreholes up to 1,000m deep, although results from the Phase 1 laboratory programme [5] indicate that the technique is unlikely to be suitable in all environments of potential relevance to RWM because of issues relating to pellet stability in saline groundwaters; see Section 6.3.2 for further discussion. Other techniques, and all techniques in boreholes up to 2,000m deep, are categorised as either **AMBER** or **RED**.

Table 6-1 and Table 6-2 indicate that high velocity and high pressure pumping of particulates are not suitable techniques for emplacement of any forms of bentonite for sealing boreholes at a site of a potential GDF. They are not considered further in this report. The remaining techniques are discussed further in subsection 6.3.2 (gravity emplacement), subsection 6.3.3 (dump bailing) and subsection 6.3.4 (conventional pumping and coiled tube pumping).
### Form of bentonite

<table>
<thead>
<tr>
<th>Emplacement technique</th>
<th>Liquid slurry</th>
<th>Suspension slurry</th>
<th>Pellets</th>
<th>Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional pumping</td>
<td></td>
<td>Proven method for placing suspension slurries. Potential for use with &lt;2 mm bentonite pellets</td>
<td>Inherently unsuitable for pumping larger particulates</td>
<td>Inherently unsuitable</td>
</tr>
<tr>
<td>Coiled tubing pumping</td>
<td></td>
<td>Proven method for placing suspension slurries.</td>
<td>Inherently unsuitable for pumping larger particulates</td>
<td>Inherently unsuitable</td>
</tr>
<tr>
<td>Gravity emplacement</td>
<td>Inherently unsuitable due to low settling speed of fine particles</td>
<td>Inherently unsuitable due to low settling speed of fine particles</td>
<td>Demonstrated using pellets. Modified approach involving coated pellets would be needed to be potentially suitable for all environments</td>
<td>Unlikely to be suitable, because of potential for bridging*</td>
</tr>
<tr>
<td>Dump bailing</td>
<td>Proven application for placing cement slurries. Can be used for bentonite slurry</td>
<td>Proven application for placing slurries. Can be used for bentonite slurry</td>
<td>Proven application for placing sand. May require positive displacement to release bentonite pellets</td>
<td>Potential application, depending on inner diameter of dump bailer relative to borehole diameter</td>
</tr>
<tr>
<td>High velocity / pressure pumping of particulates</td>
<td>Complex relative to conventional or coiled pumping</td>
<td>Complex relative to conventional or coiled pumping</td>
<td>Inherently unsuitable for pumping larger particulates</td>
<td>Inherently unsuitable</td>
</tr>
</tbody>
</table>

**Note**

* Bridging is the process by which material comes to rest in the borehole at a shallower depth than planned

**Table 6-1** Application of techniques for placing bentonite material in boreholes up to 1,000m deep: knowledge transfer from the oil and gas industry. Techniques categorised as GREEN and AMBER should be considered for application for sealing boreholes at a potential GDF site. See text for details
### Form of bentonite

<table>
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<tr>
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<td>Inherently unsuitable</td>
</tr>
<tr>
<td>Gravity emplacement</td>
<td>Inherently unsuitable due to low settling speed of fine particles</td>
<td>Inherently unsuitable due to low settling speed of fine particles</td>
<td>Potentially applicable subject to improved coating of pellets. Modified approach would be needed to be potentially suitable for all environments of relevance to RWM</td>
<td>Unlikely to be suitable, because of potential for bridging</td>
</tr>
<tr>
<td>Dump bailing</td>
<td>Proven application for placing slurries</td>
<td>Proven application for placing slurries</td>
<td>Proven application for placing sand packs. May require positive displacement to release bentonite</td>
<td>Potential application, depending on inner diameter of dump bailer relative to borehole diameter</td>
</tr>
<tr>
<td>High velocity and high pressure pumping of particulates</td>
<td>Complex relative to conventional or coiled pumping</td>
<td>Complex relative to conventional or coiled pumping</td>
<td>Inherently unsuitable for pumping larger particulates</td>
<td>Inherently unsuitable</td>
</tr>
</tbody>
</table>

**Table 6-2** Application of techniques for placing bentonite material in boreholes up to 2,000m deep: knowledge transfer from the oil and gas industry. Techniques categorised as **GREEN** and **AMBER** should be considered for application for sealing boreholes at a potential GDF site. See text for details.

#### 6.3.2 Gravity emplacement

**Pellets**

Gravity emplacement is a proven technique for placing bentonite pellets in boreholes up to 1,000m deep. The requirement is that hydration (swelling) of the bentonite pellet is delayed for sufficiently long to allow it to sink to the required position in the borehole; up to one hour sinking time for pellets in a 1,000m deep borehole. Premature swelling can result in bridging of the pellets at shallower depth or spalling, which can further reduce the settling speed and prevent the bentonite from reaching the required depth. The conventional approach to delaying hydration of pellets is through coating them, typically with a water-soluble coating such as natural resins or sodium carbonate. Commercially-available pellets claim to provide up to 90 minutes protection against swelling. Figure 6-1 shows photographs of the commercially-
available coated and uncoated bentonite pellets that were used in the Stage 1 laboratory programme [5]; see Section 7 for further details.

Figure 6-1 Close up of the commercial Pel Plug pellets. Uncoated pellets are shown to the left and coated to the right. Note the ruler has a metric scale

The technique of gravity emplacement is therefore potentially applicable for use with bentonite pellets in boreholes up to 2,000m deep, although we have been unable to find any examples. The longer sinking time (up to two hours) and greater sinking distance mean there is greater potential for bridging and premature hydration.

An aspect of Phase 2 of the current project has been a laboratory programme to investigate the performance of bentonite (as slurries, pellets and blocks) in a wide range of water compositions [5]. One component of this programme investigated the early swelling behaviour of coated and uncoated bentonite pellets, to build an understanding of their likely behaviour during emplacement in a deep borehole. Results indicated that bentonite pellets, even if coated, are physically unstable in saline water and their surfaces spall quickly. Gravity emplacement through a water column of saline water would therefore not be a suitable emplacement technique because of the much lower settling velocities of the spalled pellets. The outcome of the laboratory studies, discussed further in subsection 7.2.1, has confirmed the circumstances under which gravity emplacement might be suitable for placing various forms of bentonite.

There are two approaches for placing bentonite pellets by gravity: adding the pellet directly to the borehole and the use of a tremmie pipe, or similar. The latter approach has the main advantage that the water composition in the tremmie pipe can be controlled and the speed of emplacement increased by pumping. As a result, bentonite pellets can be emplaced more quickly in a carrying fluid of the optimum composition. Further, it is easier to take countermeasures if bridging of the bentonite occurs. As discussed in subsection 5.2.4, the groundwater composition will control the subsequent swelling behaviour of the pellet after it has reached the seal position.

Blocks

Gravity emplacement of bentonite blocks in boreholes has been suggested previously, as illustrated by patents envisaging emplacement of tapered ‘bullets’ of bentonite. However, gravity emplacement is not likely to be a suitable technique for sealing boreholes using bentonite blocks at the site of a potential GDF. Although tapering might reduce the potential for bridging, gravity emplacement is relatively uncontrolled relative to lowering a device such as a dump bailer on a wireline, coiled tubing or drill string, and there is a potential that the block becomes ‘stuck’ at borehole breakouts. Dropping the blocks inside a tremmie pipe or similar is unlikely to be suitable because there will be a large difference between the inner diameters of the tremmie
pipe and borehole. Consequently, even if the borehole is of low rugosity, the effective density of a block placed in the borehole under gravity settling will be much lower than could be achieved by other emplacement approaches.

6.3.3 Dump bailing

Dump bailers are routinely used to place cement slurries and sand to depths greater than 2,000m in boreholes. They could be used to place bentonite slurries in boreholes for sealing purposes and, subject to more substantial re-design, to place bentonite pellets and blocks.

The main advantages of dump bailers are:

- accurate emplacement of known volumes of material at known depths in the borehole. We may be confident that all bentonite has been placed at the required depth, and that no ‘bridging’ of bentonite at shallower depth has occurred. This is a particular advantage relative to gravity emplacement;

- simplicity of approach. The technology is well established and relatively simple to deploy. Material can be released at a desired depth either by gravity alone or by positive displacement (see Figure 6-2). It would be easier to demonstrate that the seal had been placed in accordance with the design than in the case of gravity emplacement;

- flexibility. Dump bailers could be used for placing a range of materials in the borehole: bentonite (as pellets and, potentially, as blocks) for sealing; graded silica or crushed rock for support elements, and; short sections of cement-based materials for placing across fracture zones. Again, this would simplify the approach to sealing boreholes;

- control of fluid environment during emplacement. Some dump bailers are designed to isolate the contents of the bailer from groundwater as the bailer is lowered in the borehole;

![Figure 6-2](image-url)  
**Schematic of an existing dump bailer with positive displacement system.** Cement is noted as the delivered material in this example; modifying a design to accommodate bentonite delivery would be needed and is believed to be practicable.
the bailer is only opened, and the contents displaced from it, when the bailer has reached the required position. This design feature could be useful as it could be used either to place pellets in a ‘dry’ form (i.e. without added water) or to add water with an optimised composition when the bailer is loaded at the ground surface. Either approach should remove the possibility of premature hydration or spalling of the bentonite pellet or block before the bailer is opened.

Because of the relatively small volumes of material that can be carried in existing dump bailers, multiple trips would be required to place sufficient bentonite to form a borehole seal; this would certainly be the case for placing seals more than a few metres long. Cost is a major consideration in the oil and gas industry, and is the major reason why dump bailers (through the use of multiple trips) are not used to place larger volumes of material in a borehole. This constraint may be less important for sealing boreholes at a GDF site, both because of the relatively small number of boreholes that will require sealing and because of benefits that dump bailers could provide in terms of accurate emplacement and simplicity of approach, thus enabling correct emplacement of the seal to be demonstrated.

Existing dump bailers used in the oil and gas industry would need to be developed to produce a dump bailer optimised for the emplacement of bentonite. This would require some further generic RDD and field trials. Although use of any dump bailer system is likely to require multiple trips to place sufficient bentonite to form a borehole seal, there is merit in developing a bailer that could place larger volumes of material in order to reduce the number of trips required. In addition, it is likely that some generic RDD would be needed to demonstrate that the bentonite can be successfully released from the bailer; this may require a demonstration that a positive displacement system can successfully push the hydrating bentonite from the bailer into the borehole.

6.3.4 Conventional pumping and coiled tube pumping

Both conventional pumping and coiled tube pumping are standard techniques used in the oil and gas industry to place slurries in boreholes. Conventional pumping is the most commonly-used technique for placing cement-based slurries. Coiled tube pumping offers advantages, particularly in terms of control of rate control, and is used for placing cement-based slurries and granular materials. Although neither technique has been used to place bentonite, both could be used to pump bentonite slurries. Liquid slurries of bentonite are the easiest application, as the bentonite is already hydrated prior to emplacement. It is also possible that the techniques could be used to pump suspension slurries of bentonite. Particle sizes would need to be small (2 mm size or smaller) and the particles would need to be coated to delay hydration and swelling during emplacement. Further, the potential for mechanical damage (‘crush’ damage) to the pellets during pumping would need to be assessed, as this could negate the effect of coatings and result in premature hydration.

Bentonite slurries will have lower placed densities, and hence (other things being equal) higher permeabilities, than either bentonite pellets or blocks. It is not clear whether, or under what circumstances, they would be suitable for forming borehole seals. The required permeabilities of borehole seals were considered previously in Section 4; in this section of the report, we are only concerned with the practicality of approaches to place bentonite in deep (up to 2,000m) site investigation boreholes at a potential GDF site.

6.4 Potential development of dump bailers

As part of the Phase 2 borehole sealing project, dump bailer manufacturers have been contacted to provide information on the specifications, deployment mechanisms and activation mechanisms of existing products. This information is compiled and reviewed in Section 2 of [33]. In summary, a number of dump bailer devices are currently available, which can be deployed on wireline, slickline, electric line and, with one particular company, on coiled tubing. The contents of the bailers are released either through gravity or by positive displacement triggered by devices such as electric line, explosives, mechanical jarring, pulling, wellbore hydrostatic pressure, plungers, blow away discs and electro-hydraulic bottom bailers.
The diameters and joint lengths of existing dump bailers come in a range of sizes, up to 140 mm external diameter and up to 4m long. The bailer sections can be connected together to increase the volume of material contained in the bailer. Existing dump bailers can therefore store and dump a wide range of volumes. These bailers have been designed to release materials that can flow out of exit ports on the sides of the bailer, and therefore are only suitable for slurry materials such as cement or bentonite drilling fluids, acids and fine aggregates such as sand. All current bailer models are unsuitable for dumping bentonite pellets or blocks. Existing dump bailers may be suitable for placing bentonite slurries, but this has not yet been demonstrated.

The second stage of the review [33] involved engagement with dump bailer tool manufacturers to determine whether existing bailer technology could be adapted to dump bentonite pellets or blocks (as cylindrical rods) accurately to a required depth within a borehole. If this was not considered practicable, suppliers were asked to provide the outline of a device that could be used for this purpose. It was specified that the bentonite should be hydraulically isolated from any wellbore fluids (drilling fluids, completion fluids, brine) while run within the wellbore and that the method for extruding the bailer contents, whether by gravity or positive displacement methods, be described.

Four suppliers responded and were all confident that modified or new dump bailers could be designed to meet the requirements. The most promising approaches involved deploying the dump bailer on coiled tubing and using a back pressure exerted by fluids pumped down the coiled tubing to extrude the contents of the bailer using a piston.

Separately, the approach of deploying a dump bailer using core drilling equipment has been considered [7]. Early attempts to displace sealing materials in boreholes using a core barrel were described in [34] and summarised in subsection 6.4 of [7]. An updated conceptual design based on the wireline system SK 5¾” was presented in subsection 6.4.1 of [7], following discussions with a manufacturer of wireline drilling equipment for deep boreholes. A modified core barrel, up to 9m long, could be used to place bentonite pellets and blocks. The bailer (equivalent to the inner core barrel) is gravity driven or pumped to the bottom of the drill string, where it seals against the outer core barrel. Fluid is then pumped into the wireline core string to push a piston into the bailer and displace the contents. Finally, the system could be used to further compact pellets after their release from the bailer. See subsection 6.4 of [7] for a more detailed description of this system.

In conclusion, following discussions with drilling equipment manufacturers, the project has confirmed that using dump bailers to place bentonite pellets and blocks in deep site investigation boreholes is conceptually achievable. Bailers could be deployed on coiled tubing or on core drilling equipment. Each approach has its advantages. Deployment on core drilling equipment would be robust and would allow emplacement of sealing materials to be interspersed with drilling operations, for example to ream out casing. In addition, after emplacement of the bentonite, the bailer (inner core barrel) could be replaced with a wireline compacting system that could tamp down the bentonite in the borehole to increase packing density. Deployment of coiled tubing would require less equipment at the wellhead, and would be better suited to interspersing emplacement of bentonite pellets or blocks with emplacement of pumpable materials such as cement or graded silica for support elements. Further discussion of the coiled tubing approach is given in Section 5 of [4].
Dump bailers should be used to place bentonite as blocks or pellets for borehole seals. The project has identified that suitable dump bailers can in theory be developed for this purpose. We recommend that further RDD be undertaken to demonstrate the technology.

Bentonite slurry for borehole seals could be placed by conventional pumping using drill pipe, pumping using coiled tubing or by using dump bailers. The choice of technique will be influenced by factors such as borehole stability and the length of bentonite seal to be emplaced.
7 Experimental programme to build understanding of aspects of bentonite behaviour in borehole seals

7.1 Introduction

A substantial knowledge base exists on the use of bentonite as sealing materials and backfill in the EBS of a GDF. In many areas, this knowledge is applicable to the use of bentonite in borehole seals. However, it is important to recognise the differences between a deep site investigation borehole and the EBS of a GDF. The main differences between placing bentonite in a borehole and in an EBS of a GDF are that:

- the geometry of space in a borehole (where bentonite needs to be transported over distances up to 2,000m to fill openings with diameters less than 0.1m) is more difficult to fill than the openings in an EBS, which are typically on the scale of metres or tens of metres;
- a deep site investigation borehole will generally be filled with water at the time of sealing whereas the openings in a GDF will be air-filled when bentonite seals or backfills are placed;
- bentonite placed in a deep site investigation borehole is likely to encounter a wider range of groundwater compositions than in an EBS (by virtue of the fact that the borehole extends from ground surface to a depth of up to 2,000m), and hence understanding of bentonite behaviour in a wider range of groundwater compositions will be required;
- there will be less opportunity to determine the performance of an emplaced seal in a borehole, because of very limited accessibility.

A laboratory programme has been undertaken as part of the Phase 2 borehole sealing project to determine properties of bentonite relevant to emplacement and sealing performance in deep boreholes. The design of the laboratory programme was developed in the early part of the project (Task 4; see Figure 1-1), after a decision on materials for use in borehole seals had been reached; see subsection 5.2.1.

The main focus of the work undertaken in Stage 1 of the laboratory experimental programme (designated as Task 6) has been on the use of bentonite pellets, because these are potentially suitable for sealing boreholes in a wide range of geological environments. Some tests were also made on bentonite slurries and highly compacted bentonite blocks. This work is described in subsections 7.2 and 7.3. In Stage 2 of the laboratory experimental programme (designated as Task 7), a series of larger-scale experiments have been undertaken to investigate the performance of seals formed from bentonite blocks and pellets. These larger-scale experiments are described in subsection 7.4.

7.2 Bentonite behaviour during emplacement in the borehole

A general concern with using bentonite pellets or blocks to seal boreholes is that they will start to swell during emplacement and could ‘bridge’ in the borehole before reaching the target emplacement depth. To mitigate this effect, ‘coated’ bentonite pellets are often used in borehole sealing applications. The objective of the typically water-soluble coating is to delay early water uptake and swelling of the pellet, and thereby reduce the possibility that bentonite pellets become stuck in the borehole (‘bridge’) before they sink to the planned sealing depth.

An alternative approach, used by the oil and gas industry to minimise or prevent swelling of bentonite-based drilling muds, is to control the chemistry of the drilling fluid. We recognise that the oil industry’s experience of controlling the swelling of clay minerals generally involves clay slurries, which are initially water saturated. This is different from applications using bentonite
pellets and blocks (and suspension slurries, if such materials are practicable for use in borehole sealing), where the bentonite is not initially fully saturated and where contact with highly saline waters is known to cause pellets to disintegrate. The project has investigated whether higher salinity fluids could have a role in facilitating the emplacement of bentonite pellets in boreholes.

Experiments were therefore undertaken in the Stage 1 laboratory programme using both coated and un-coated bentonite pellets and blocks to investigate early swelling, settlement and erosion behaviour. The impact of water composition on the early swelling behaviour of bentonite pellets and on the rheology of bentonite slurries was also investigated. The tests were designed to provide information on the range of environmental conditions (such as groundwater salinity) and borehole depths for which the different emplacement approaches could be feasible. The work is described in detail in [5] and is summarised below.

7.2.1 Pellet tests

Types of pellets used in the experiments

Both commercially available bentonite pellets and bentonite pellets that were manufactured within the project were used in the experiments. The commercial pellets, Pel-Plug, are available as coated and un-coated types; the former have biodegradable water-soluble protective coatings that the manufacturer asserts will withstand 30 minutes exposure in water (for TR-30 pellets) or 60 minutes exposure (for TR-60 pellets). These pellets are illustrated in Figure 6-1. The manufacturer did not qualify the statement by specifying a particular water chemistry and, as will be shown later in this report, the stability of the commercially coated bentonite pellets is sensitive to this factor. TR-90 pellets are also available, with claimed 90 minutes resistance to exposure to water, but these were not available to purchase at the time of the experiments and were therefore not included in the study.

Two types of roller-compacted pellets formed from MX-80 bentonite were produced as part of the project: pillow-shaped pellets (15 x 15 x 8 mm) and almond-shaped pellets (30 x 20 x 14 mm). In addition to the different shapes, the pellets have been manufactured with raw material having different water contents to produce pellets with different densities and degrees of saturation.

It is important to recognise that the bentonite pellets used in the tests reported here and in subsection 7.4 have not been optimised to maximise their emplaced density. The use of pellets with different shapes and sizes, including the use of pellets with a range of sizes, could result in different, and potentially greater, placed densities to those reported here.

Sinking speeds

The sinking speed of bentonite pellets in a water-filled tube was determined by laboratory tests. The tests showed that all pellet types reached a constant sinking rate very soon after dropping. The average sinking rates for the different pellets varied between 0.30 - 0.45 ms\(^{-1}\) (1.0 – 1.6 km per hour). Hence, water-soluble coatings are unlikely to be able to protect against hydration and onset of swelling before the bentonite has sunk to the bottom of a 2 km deep borehole.

Early swelling behaviour

The early swelling behaviour of bentonite pellets in a range of aqueous solutions (from tap water to 1M solutions of Na, K and Ca) was investigated with two types of tests; small-scale tests in pots and larger-scale tests in plexiglass tubes to simulate sections of borehole. Results from one set of small-scale tests after 10 minutes exposure to the solutions are shown in Figure 7-1. The full set of results is presented in Appendices F to Q of [5]. The experiments provided much information that is important for borehole sealing design. The following observations and conclusions were drawn from these tests.

1. When dropped into water, bentonite pellets start to absorb water and swell. In more saline solutions, pellets start to disintegrate quickly. Both types of behaviour will affect the potential for pellets to sink through the water column in a borehole. They decrease the sinking rate and increase the risk of bridging, hindering other pellets from sinking through the water.
2. Three methods have been investigated with the objective of decreasing the early swelling behaviour: manipulation of the water chemistry (using higher salinity solutions); using pellets with a high degree of saturation; and, applying a coating layer on the exposed surfaces.

a. Manipulation of the water chemistry. Early in the project, it was suggested that strong saline solutions could prevent the bentonite from swelling. This is the case in the long term, but in the short term the transport of water into the pellets is faster, which results in pellets physically disintegrating; for example, see Figure 7-1. It was found that using low salinity solutions was the best way to prevent early swelling.

b. High degree of saturation. From the test results it is clear that the higher the degree of saturation of the pellets, the more resistant to early swelling they will be when dropped into water. The effect seems, however, not to be strong enough for the purpose of borehole installation.

c. Coating. The effect of applying a coating layer on the exposed pellet surfaces in order to delay the early water uptake seems to function well. Tests have been performed with both single layer coated pellets and double layer coated pellets; the positive effect of an extra coating layer is clear. However, when the commercially coated pellets were exposed to water with salt concentrations of 0.1 M and higher, they are strongly affected by disintegration after only 30 minutes.

3. The salinity of the water strongly influences the pellet behaviour. The tests performed in 1M solutions (Na, K and Ca) showed that all pellets disintegrated soon after coming into contact with these solutions. This behaviour would preclude placing bentonite seals in a saline water-filled borehole by dropping pellets from surface and allowing them to sink through the standing water column in the borehole. One conclusion from the tests is that if bentonite pellets are to be installed by gravity emplacement in such a borehole, the installation process will only be practicable if it is possible to change the water in the borehole to freshwater during the installation process.

4. The main cation type present in the water seems to be of less importance than the salinity. However, in the tests performed with CaCl₂ (0.1 and 1 M), the disintegration of the pellets seemed to be somewhat faster than in tests with 0.1M NaCl or KCl.

The overall conclusions from these experiments were that gravity emplacement of bentonite pellets by dropping them into a borehole from the surface would require that the water column in the borehole was of low ionic strength (freshwater) and probably also that an improved pellet coating would be needed to delay swelling.

**Ability to fill irregular-shaped boreholes**

The ability of bentonite pellets to fill irregular-shaped wellbores was investigated by experiments that simulated a borehole section where rock 'breakout' has resulted in a section of borehole with enlarged diameter. The tests (e.g. Figure 7-2) showed that bentonite pellets would largely fill the enlarged section of borehole. The degree of pellet filling will, however, be lower in comparison with sections with nominal borehole diameter because of the friction between the pellets and between the pellets and the walls. In a dry tube, the degree of filling was found to be between 89% and 94% depending on pellet type. In a water-filled tube, the degree of filling was considerably lower, between 57% and 82%. The lower degree of filling in the water-filled tube is believed to depend on the fact that water rapidly affects the pellet surfaces and increases the friction angle. Two main conclusions were drawn from the tests.

- Smaller pellets fill up larger diameter sections more efficiently. These pellets seem to flow out into the larger section more easily.
- It is considerably easier to fill up sections with larger diameter in dry conditions. Water rapidly affects the pellet surfaces, which become 'sticky'. Consequently, the pellets do not flow out into the larger diameter sections as effectively as in dry conditions.
Figure 7-1 Pel-plug pellets (uncoated, TR30 and TR60) exposed to different water solutions. The photographs are all taken after 10 minutes exposure.
7.2.2 Bentonite slurry tests

The advantage of slurries is that they are easy to install and easily fill up all irregularities, such as breakouts, in the borehole. The rheological properties of bentonite slurries (‘liquid slurries’ in the terminology of Section 6, formed by mixing finely dispersed bentonite powder with water) have been investigated to find the highest densities that can be pumped. The water content, the salt type and the salt concentration have been variables. High salinity (>1M) effectively reduces swelling of bentonite. This limits the extent to which the grains of MX-80 expand. Although it is well known that Ca-montmorillonite has finite swelling, the work presented in [5] showed that at high ionic strength, NaCl prevents expansion better than CaCl₂.

The experiments confirmed that potassium acts as a swelling inhibitor. Dispersing MX-80 powder in 2M KCl gave a slurry with maximum yield stress of just 45 Pa, even at 100% water content. With NaCl, the lowest tested water content was 106% at a NaCl concentration of 3M. The maximum yield stress for such a slurry was about 80 Pa. With the criterion adopted in the
present work that the maximum allowed yield stress is 100 Pa, it is thus possible to prepare MX-80 slurries in KCl with water content below 100%. This is probably also true using NaCl if the concentration is increased above 3M, which was the highest concentration used in this study. A water content of 100% corresponds to a dry density of about 730 kg/m$^3$. This is clearly lower than the possible dry densities that can be achieved using pellets. On the other hand slurries would be less sensitive to surface roughness and rugosity.

7.2.3 Block installation tests, to simulate bentonite erosion during emplacement

In boreholes with uniform diameter, the highest placed bentonite density is achieved by installing cylindrical high density bentonite blocks. A problem may be loss of bentonite by erosion during installation. In order to study this, a number of erosion tests simulating installation of high density MX-80 bentonite blocks in boreholes have been performed.

Cylindrical blocks of bentonite were manufactured and machined to diameters of 94 mm or 96 mm depending on the target for the annular gap between the curved surface of the bentonite block and the wall of the simulated borehole (2 mm or 3 mm). This annular gap was considered in subsection 3.4.2 of [4] to be the minimum that the oil and gas industry would accept when running packers into an un-cased borehole. By analogy, we considered it the minimum gap between the bentonite block and the borehole wall.

The blocks were coated with four coats of shellac$^{17}$ because previous small-scale tests indicated that this would be sufficient for one hour of exposure to freshwater. The blocks were placed in a flow rig of inner diameter 100 mm with cones covering the end surfaces so that only the curved surface was exposed to the flowing water. Freshwater was flushed past the exposed block surface at a rate of 1 litre per second for one hour; this flow rate and time corresponds to lowering the bentonite block a distance of 460m in a 100 mm diameter borehole, assuming that all water standing in the borehole passed through the annular gap between the block and the borehole wall.

Variables in the tests were: degree of saturation of the bentonite block; gap width between the block and the wall of the simulated borehole, and; whether or not the block has been coated. The results of the erosion tests are presented in Table 7-1.

<table>
<thead>
<tr>
<th>Annular gap</th>
<th>Uncoated block</th>
<th>Coated block (shellac)</th>
<th>Uncoated block with high initial saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm</td>
<td>7.7%</td>
<td>1.1%</td>
<td>4.4%</td>
</tr>
<tr>
<td>3 mm</td>
<td>5.3%</td>
<td>0.8%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

Table 7-1 Percentage mass loss from bentonite blocks after erosion tests

The main conclusions from the tests are:

coating with shellac greatly reduces the loss by erosion;

a larger annular gap between the block and tube wall reduces erosion losses, most likely as a result of the lower flow velocity;

the lowest erosion was achieved with a combination of coated blocks and the larger annular gap. However, the highest as-placed density was achieved with the coated block and the

$^{17}$ Shellac is an organic resin harvested from secretions of the lac bug. It is dissolved in ethanol to form the varnish that is used to coat the bentonite block and prevent immediate hydration on contact of the block with water. Unlike the coatings used in the pel-plug bentonite pellets, the shellac is not considered to be water soluble. The coating will therefore remain as an impurity after it has flaked away from the surface of the block.
smaller annular gap because the additional mass present in the larger diameter block more than compensated for the additional mass lost by erosion.

A high degree of initial saturation results in lower erosional loss, but the resulting installed density of the block was still lower than for standard blocks because of the problems of compacting such blocks to high density.

One final point to note is that the tests were carried out in an ‘ideal’ borehole with the water moving past a stationary block. In reality, the bentonite block will need to be lowered in the borehole and hence could be abraded by contact with the borehole wall. This would lead to abrasion of surface coatings and hence premature hydration and increased bentonite loss. For these reasons, it was recommended in subsection 6.3.3 that dump bailers be used to place bentonite slurries, pellets and blocks in deep boreholes.

7.3 Bentonite behaviour after emplacement. Influence of water composition on swelling pressure and hydraulic conductivity

7.3.1 Test procedure

A series of six laboratory experiments was undertaken to study the impact of varying water composition on the swelling pressure and hydraulic conductivity of MX-80 bentonite samples with dry densities ranging from 820 kg/m$^3$ to 1530 kg/m$^3$. The MX-80 pellets, which are quite large relative to the size of the test cells, were crushed to smaller grain sizes before being poured into the sample holders (Figure 7-3); this was done to facilitate compaction and homogenization during water uptake.

![Figure 7-3](image)

**Figure 7-3** Upper left: pellet material placed in the test cell with the lowest density during preparation. Lower left: partly crushed pellet material in the test cell with the highest density during preparation. Right: Test cell setup during equilibrium phase with a test solution

For each test sample, a specified mass of bentonite was placed in the test cell, which had a diameter of 35 mm. Distance pieces (‘spacers’) were placed between the piston flange and the sample cylinder ring in order to produce a sample height (H) of 10 mm, and thereby produce a sample with the required density. Additional compaction on loading the sample was only needed
to further crush/consolidate the higher density samples. The piston, pressure transducer and upper lid were attached and fixed (Figure 7-4).

De-ionized water was slowly circulated intermittently behind the bottom filter, in order to start the water saturation from the bottom face of the sample and to let air out through the upper filter. After approximately one week, water was also intermittently circulated in the upper filter. When equilibrium pressure had been achieved, or was close to being achieved, hydraulic conductivity (k) was measured by applying a hydraulic gradient across the sample and measuring the resultant flow rate.

![Sketch of the test cell setup during an equilibration phase. The test solution reservoir was removed during hydraulic conductivity measurements and the test solution in the lower filter was pressurized. Both inflow and outflow was registered.](image)

After the initial measurements with de-ionized water, the test solution were changed to 1 M NaCl, which was circulated until near-equilibrium swelling pressure was reached. Hydraulic conductivity was then determined for the new boundary conditions. This procedure was then repeated for a sequence of water compositions including 1M and 0.05M NaCl, 1M and 0.05M KCl solutions, and finally 1M and 0.016M CaCl$_2$ solutions (Figure 7-5). The use of 0.016M CaCl$_2$ was motivated by the ionic strength, which is equal to the 0.05M solutions of NaCl and KCl. An extra exchange was made between the KCl and the CaCl$_2$ cycle by use of NaCl solutions in order to ensure that potassium could be replaced by sodium despite the lower selectivity for sodium. The time period to reach near-equilibrium conditions was calculated from consideration of one dimensional solute diffusion through the bentonite under constant boundary conditions set by the external solution. An ion exchange of more than 80% was calculated in the central part of the samples after twenty days$^{18}$.

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$^{18}$ As previously stated, approach to equilibrium in these tests was also evaluated during the experiments by monitoring the swelling pressure and its stabilisation. It would only have been possible to determine the composition of the ion exchanged cations at the end of the final phase of the test. However, this was not done.
At test termination, each sample was removed and water content and bulk density were measured. The release of confining pressure during the dismantling of the test cells generally leads to a minor water uptake from the filters. Fast and consistent handling during the dismantling of the samples was the only countermeasure taken to minimize this possible artifact.

7.3.2 Results and discussion

The swelling pressure stabilized in all six samples within a week of the start of the saturation process. The samples were left for another 30 days, during which the pressures were almost constant. The measured swelling pressures are in good agreement with previously published results for both pelletized and non-pelletized MX-80 bentonite.

The measured swelling pressures and calculated hydraulic conductivities from the matrix of experiments are shown in Figure 7-6 and Figure 7-7. Measured equilibrium swelling pressure correlates positively with the dry density of the sample; the actual swelling pressure at any initial dry density is influenced by the water chemistry.

Figure 7-5 Full test cycle with pressure response as a function of time. Arrows indicate changes of test solution. Short term pressure spikes are due to external water pressure mainly in conjunction with measurement of hydraulic conductivity. Legend shows test cell numbers.
Figure 7-6  Measured swelling pressure versus dry density for all samples subsequently exposed to the various test solutions (from top to bottom). DI indicates de-ionized water, and M indicates molar concentration.

Figure 7-7  Measured hydraulic conductivity versus dry density for all samples subsequently exposed to the various test solutions (from top to bottom). DI indicate de-ionized water, and M indicate molar concentration.

7.3.3 Conclusions of experiments

Two main conclusions can be drawn from the series of tests to investigate the influence of water composition on bentonite swelling pressure and hydraulic conductivity. Ion exchange between Na, K and Ca is reversible under the test conditions and, from the observed stabilisation of swelling pressures in the fixed volume cells, occurs on the timescales predicted from diffusion calculations. This builds confidence in the assertion that the swelling pressure and hydraulic conductivity of a bentonite seal will be controlled in the longer-term by the composition of the groundwater in contact with the seal rather than by the composition of the water used during seal emplacement.

The logarithm of hydraulic conductivity decreases linearly with the dry density of the bentonite; the logarithm of swelling pressure increases linearly with the dry density of the
bentonite. The actual values of hydraulic conductivity and swelling pressure for any given dry density are dependent on the water composition; see the results presented in Figure 7-6 and Figure 7-7. For any given cation, swelling pressure decreases and hydraulic conductivity increases with increasing cation concentration. When contacted with 1M solutions, hydraulic conductivity of the bentonite increases in the sequence Ca, Na and K. The results are in broad agreement with previously published results.

The hydraulic conductivity and swelling pressure of a bentonite seal will be controlled by the emplaced dry density of the bentonite and the composition of the groundwater in contact with the bentonite. These relationships, and knowledge of the range of emplaced densities that can be achieved using different forms of bentonite (blocks, pellets and slurries) can be used to determine which emplacement techniques and forms of bentonite can achieve the required hydraulic conductivity for a borehole seal.

7.4 Large-scale laboratory experiments to determine properties of bentonite seals

7.4.1 Experimental set-up

Task 7 of the Phase 2 borehole sealing project, reported in [6], was the second stage of a programme of laboratory experiments. It consisted of three large-scale tests that simulated the emplacement of bentonite seals in 3m long sections of water-filled borehole.

- Pellet test 1. MX-80 pellets installed in a borehole filled with water with a salinity of 0.5M NaCl. Test duration was 62 days.
- Pellet test 2. MX-80 pellets installed in a borehole filled with water with a salinity of 0.1M NaCl. Test duration was 56 days.
- Block test 1. Compacted blocks made of MX-80 bentonite were installed in a borehole filled with water with a salinity of 0.5M NaCl. Test duration was 147 days.

The water composition for Pellet test 1 and Block test 1 was chosen to be 0.5M NaCl, equivalent to 29,000 mg/L total dissolved solids. This composition, similar to that of seawater, was chosen as a reasonable compromise for groundwater composition in HSR at GDF depth; see Table 2-2, where groundwater composition in a range of HSR environments is discussed. The water composition for Pellet test 2 was chosen to be 0.1M NaCl (5,800 mg/L total dissolved solids), similar to measured groundwater compositions at the depth of planned repositories outside the UK in environments where HSR extends to ground surface.

The experimental set-up for the pellet tests is shown in Figure 7-8. The apparatus is formed from sections of plexiglass tubing, totalling 3m in length. Most sections have inner diameters of 166 mm or 170 mm; the smaller diameters are the result of being lined with permeable filter mats that are connected to inlet and outlet valves and which act to allow water to flow into or out of the bentonite at these horizons. They simulate water-bearing fracture zones in the borehole, and provide the source of water as the bentonite re-saturates during the test.

Two sections in the simulated borehole have larger diameter (186 mm and 236 mm), and simulate zones of breakout in the borehole. From results presented in subsection 7.2.1 and illustrated in Figure 7-2, the initial density of bentonite filling these ‘breakouts’ is expected to be lower than that filling sections of borehole with the smaller diameter.

Radial swelling pressure was measured at various positions in the column (see Figure 7-8). Axial swelling pressure was measured at the top of the borehole. Inflows and outflows of water
occurred through various inlet and outlet valves at different stages in the test, and were measured using a GDS Instruments Advanced Pressure/Volume Controller.

The set-up for Block test 1 was similar, but the apparatus was largely manufactured from stainless steel, in anticipation of the higher swelling pressures that would be generated on resaturation.

Figure 7-8  Left: Schematic drawing of the large scale demonstration test with pellets. The sparsely rasterized surfaces show the sections lined with filter mats. Right: photograph of the set up for Pellet test 1
The procedure in each of the three tests was similar. The 3m long ‘boreholes’ were filled with 0.1M or 0.5M NaCl, and then filled to the top with bentonite pellets or blocks. The top of the ‘borehole’ was then sealed to prevent axial swelling, and resaturation of the bentonite monitored by measuring the swelling pressures at different positions in the tube. During resaturation, a hydraulic pressure of 100 kPa (10m head of water) was applied to all water inlet valves and the cumulative inflow measured as a function of time.

When resaturation was complete, hydraulic tests were made at various points in the tube by establishing hydraulic gradients across sections of bentonite and measuring the resultant flows over durations up to 240 hours (for pellet tests) or 1,000 hours (for the block test). Hydraulic conductivity was then calculated, as described in subsections 4.6, 5.6, 6.6 and Appendix 1 of [6]. The experiments were then dismantled and the bentonite sub-sampled to determine moisture content, density and degree of saturation as a function of location in the tube. This provided information on the extent of homogenisation that had occurred by the end of the experiments.

A visual inspection was also undertaken immediately before and during the dismantling of the experiments to identify any areas where the bentonite had not fully filled the tube and the presence of any relict pellet structures. This provided further information on the extent of bentonite homogenisation in the experiments.

### 7.4.2 Results of tests with bentonite pellets

As expected, the results showed that the swelling pressure and hydraulic conductivity of this rather low density bentonite (dry density of 800-850 kg/m$^3$) was sensitive to water composition. The bentonite in pellet test 1, which was performed in 0.5 M NaCl, achieved a low swelling pressure (0-30 kPa). The calculated hydraulic conductivities were in the range of $1 \times 10^{-9}$ ms$^{-1}$ to $3 \times 10^{-9}$ ms$^{-1}$. The bentonite in pellet test 2, which was performed in 0.1 M NaCl, achieved a swelling pressure of between 20-60 kPa. The calculated hydraulic conductivities for this test were between $8 \times 10^{-11}$ ms$^{-1}$ to $2 \times 10^{-10}$ ms$^{-1}$; that is, about ten times lower than in pellet test 1.

Measurements made when the experiments were dismantled indicated that the bentonite in the tube was fully saturated in each test. Visual observations made before the experiment was dismantled show that both the voids between pellets and the larger voids in the upper parts of the simulated breakouts had been closed. Likewise, the bentonite had sealed against the borehole wall along its entire length. Homogenisation of the pellet fillings after the two month tests was extensive, although it was still possible to identify the relics of individual pellets as darker areas in the saturated filling when the experiment was dismantled (Figure 7-9).

![Part of the bentonite surface from pellet test 1 (section with diameter 166 mm). The photo shows clearly the heterogeneity of the bentonite where it is still possible to identify relics of individual pellets as dark spots](image-url)
The differences in the colour of the bentonite in Figure 7-9 are believed to be the result of small difference in density and water content.

The calculated dry densities were in general lower close to the simulated borehole walls (Figure 7-10). The densities in the ‘breakout’ sections were not noticeably lower than in the smaller diameter sections, with the exception of the upper surface, where larger voids were observed immediately after the bentonite pellets had been poured into the tubes. At the end of the tests, these voids had been filled with a low density bentonite gel.

Granular materials are known to exhibit a higher void fraction (or equivalently, lower density) close to the wall of a container, here analogous to the wall of a borehole. This is because the packing structure of the particles is affected by the presence of the wall. This effect has been studied extensively in the literature and is known as the wall effect. It is described in subsection 3.3.3 of [4]. We believe the radial density gradients at the end of the pellet experiments are due to this effect; in the longer term, we believe that further homogenisation will take place and reduce the gradient. However, as explained in subsection 8.3.1, the extent of this longer-term homogenisation is uncertain.

7.4.3 Results of the block test

The block test involved installation of bentonite blocks with diameters of 137.5 mm in a ‘borehole’ of nominal diameter 157.5 mm. The annular gap (10 mm) is considered to be similar to that required if the bentonite blocks were to be placed in the borehole using a dump bailer. The test was performed in 0.5M NaCl.

The equilibrium swelling pressure at the end of the resaturation phase varied between 400 kPa and 1,000 kPa, being lower in the larger diameter section of borehole. Calculated hydraulic conductivities determined in two sections of borehole were about $4 \times 10^{-12}$ m s$^{-1}$.

The dry densities determined at the end of the test varied between 1,150 kg/m$^3$ and 1,500 kg/m$^3$ for the nominal diameter sections and between 1,000 kg/m$^3$ and 1,250 kg/m$^3$ in the largest diameter section of tube. In all sections of tube, the highest densities occurred in the central parts of the simulated borehole and the lowest densities occurred close to the ‘borehole’ wall. Based on the calculated saturation of the bentonite (determined from the measured moisture contents and dry densities), the bentonite was considered to be fully saturated by the end of the test. At the end of the five month test, bentonite in all sections of borehole had sealed against the walls of the tube; no voids were visible$^{19}$.

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$^{19}$ The block packages started to crack after removal from the tubes, probably as a result of expansion following removal of the confining pressures.
Figure 7-10  Graphs showing the results from the determinations of the dry density in the different sections from pellet test 1. Upper: sections with a diameter of 166 and 170 mm respectively. Middle: sections with a diameter of 186 mm. Lower: section with a diameter of 236 mm.
7.4.4 Conclusions from the three large-scale tests

The swelling pressures and hydraulic conductivities evaluated from the large-scale tests are somewhat different compared to the smaller-scale fixed volume tests presented in subsection 7.3. The swelling pressures are lower and the hydraulic conductivities higher in the large-scale tests. There are two main reasons for these differences.

► The bentonite in the large-scale tests may not have homogenized to the same degree as in the small-scale tests. If this was the case, it would result in lower bentonite density at the walls of the simulated boreholes. It would also likely result in higher water flow during the experiment in this part of the tube, because of the expected higher hydraulic conductivity of the lower density bentonite. However, the measured density differences across the diameter of the tubes are not large and the effects on the hydraulic conductivity in the block and pellet experiments are estimated to be less than a factor three. Differing degrees of heterogeneity cannot explain the observed higher hydraulic conductivities in the large-scale experiments.

► It takes a longer time to reach chemical equilibrium across the bentonite in a large-scale test than in a small-scale test. During the saturation process, the salt concentration in the bentonite will be higher than at equilibrium. It will take longer for diffusive equilibrium to be established throughout the larger samples, and hence these samples may retain higher salinity water in their pores during the test. The higher than expected salinity in the bentonite porewater in the large-scale tests may account for the higher hydraulic conductivity. Thus, the hydraulic conductivity of the bentonite in the large-scale tests may have reduced if the experiments had been run for longer; the measured hydraulic conductivity may be considered an upper bound of the longer-term property.

Notwithstanding this complexity, it should be noted that the measured hydraulic conductivities in the large-scale tests are all low, and are significantly lower than the hydraulic conductivities that might be required to seal deep site investigation boreholes in HSR. We therefore conclude that the performances of the bentonite in these large-scale tests would be suitable for the purposes of borehole sealing. Further, as noted previously, the pellet morphology used in the experiments is unlikely to be optimum to achieve the highest placed density.

20 The hydraulic conductivities of different regions in the bentonite seal were estimated using the observed relationship between emplaced dry density and hydraulic conductivity shown in Figure 7-7.
8 Issues affecting the evolution of bentonite properties and the longevity of bentonite seals

8.1 Introduction

After emplacement in the borehole, bentonite pellets or blocks will re-saturate by uptake of water from within the borehole and from the rock surrounding the seal. A swelling pressure will develop during the resaturation process, and an equilibrium swelling pressure will be achieved when resaturation is complete. During this process (water saturation and swelling until pore pressure equalisation), the bentonite will homogenise. In the longer term, in the order of years or more after resaturation is complete, the bentonite may continue to homogenise through creep; this is the third phase of the bentonite swelling and homogenisation process.

The ultimate degree of homogenization of bentonite is restricted by friction in the bentonite and between the bentonite and confining surfaces. This means that at equilibrium, after homogenization has gone as far as possible, there may still be density gradients and areas of lower density in the bentonite.

The main features of the bentonite swelling and homogenisation process are discussed below.

1. The swelling pressure attained when the bentonite has saturated will be controlled by the initial dry density of the bentonite, assuming the volume of the bentonite is fixed because of the confining presence of the overlying and underlying support elements, and by the composition of the water that was used during emplacement of the bentonite in the borehole. As discussed in subsection 7.2.1, the water composition during emplacement might be manipulated to facilitate the emplacement of the bentonite.

2. In a short timescale after emplacement, potentially as short as a few tens of years (see subsection 6.2 of [1]), diffusive equilibrium will be established between the solutes in the pore space of the bentonite seal and solutes in the surrounding groundwater. Assuming an equilibrium exists between adsorbed cations on the surface of the clay minerals and dissolved cations in the pore space of the bentonite, the composition of the adsorbed ion exchange complex on the clay surface will also change. Thus, in a relatively short timescale after emplacement, the swelling properties and hydraulic conductivity of the bentonite will be controlled by the composition and salinity of the groundwater. (It is worth noting that the timescale is likely to be much shorter than in the case of the EBS, where the use of larger volumes of bentonite is envisaged in some disposal concepts)

Experiments to confirm that swelling pressure and hydraulic conductivity respond to changing water composition are presented in subsection 7.3. These experiments also provide a matrix of results that can be used to determine the minimum dry density of bentonite required to achieve a specified hydraulic conductivity in a given water composition. As the maximum achievable dry density at emplacement is influenced by the form of bentonite (block, pellet, slurry), the results also indicate the forms of bentonite that would be potentially suitable to achieve the required hydraulic conductivity.

3. In the cases of pellets and blocks, the density of the bentonite on emplacement would be heterogeneous. For pellets, small-scale heterogeneity would arise because the individual bentonite pellets have voids between them. Larger-scale heterogeneity of pellets is likely to occur in boreholes with variable diameter (or ‘rugosity’); in these circumstance, the bentonite pellets may not fully fill areas of borehole with larger diameter. In the case of bentonite blocks, heterogeneity at emplacement arises because there will be an initial annular gap between the block and the borehole wall to facilitate emplacement of the block.
4. On the much longer timescale, natural geosphere evolution processes driven by tectonism and climate change will occur. Reference [35] provides a discussion of these natural processes in the context of deep geological disposal of radioactive waste in the UK. In some geological environments, these processes may result in groundwater compositions changing with time; as previously, the composition of the adsorbed ion exchange complex on the clay surface and the swelling pressure exerted by the bentonite would also be expected to change. One particular aspect of evolving groundwater compositions is of particular relevance to bentonite seals; it is possible that dilute groundwaters could penetrate to depth in some areas during periods of glaciation. In these circumstances, the potential for chemical erosion of bentonite from borehole seals should be considered. Note that there are no identifiable erosion vulnerabilities associated with any future increases in groundwater salinity.

In the remainder of this section, we consider issues affecting the evolution of bentonite properties and the longevity of bentonite seals. With regard to bentonite properties, we are concerned with swelling pressure and hydraulic conductivity. These are the properties that determine the effectiveness of the seal against flow of groundwater and, in some cases, flow of gas.

1. The first issue is erosion of bentonite (subsection 8.2), which would result in loss of bentonite from the borehole with potential decrease in swelling pressure and increase in permeability of the remaining bentonite.

2. The second issue (subsection 8.3) is that inhomogeneities could remain in the bentonite after the homogenisation process, which was described above, has been completed. For bentonite seals in boreholes, the effective hydraulic conductivity of a heterogeneous bentonite seal is likely to be higher than were the same amount of bentonite in the seal to be distributed homogeneously. Thus, it is important to understand the implications of heterogeneity, especially if the groundwater has a high salinity.

3. The third issue (subsection 8.4) is that longer-term chemical alteration processes could affect the mineralogical stability of the swelling clay component in bentonite and impair its swelling pressure and sealing properties. Further detail is given in Section 5 of [12].

### 8.2 Erosion of bentonite

In nature, erosion of soil or rock may be caused by wind, water or other natural agents. For bentonite in a sealing or buffer system, flowing water and gravity are the main causes for erosion. In the radioactive waste management context there is a tendency to divide erosion into two subcategories: ‘chemical erosion’ and ‘mechanical erosion’. These are discussed in subsections 6.2 and 6.3 of [12], and are summarised below.

#### 8.2.1 Mechanical erosion

The cause of mechanical erosion of bentonite is the hydrodynamic detachment of larger aggregates of clay layers and accessory minerals from the bentonite surface by flowing water. Mechanical erosion could lead to unacceptable material losses in regions of the borehole where groundwater inflows and outflows were high during seal emplacement, or subsequently. It is for this reason that bentonite seals will not be emplaced across flowing zones in boreholes or used to seal other higher permeability sections of rock, and why support elements placed across flowing zones require some short-term low permeability to minimise flow through the bentonite seal as it is placed. Thus, the issue of mechanical erosion of bentonite can be avoided by design.

#### 8.2.2 Chemical erosion

Chemical erosion of bentonite is erosion that occurs in dilute groundwater due to a ‘paste-to-sol’ phase transition. This type of erosion is inherent to the bentonite material. Water chemistry is important for determining when chemical erosion could be an issue. For salinities above the
critical coagulation concentration (CCC, up to 20 mM NaCl for homoionic Na-montmorillonites, which are most susceptible to chemical erosion), this type of erosion can be disregarded. However, the gel that prevents sol formation disintegrates when salinity is below the CCC. Under these circumstances, the montmorillonite will erode due to the formation of sol, and could be transported away from the sol – gel interface by gravity or flowing groundwater. Quantifying erosion of montmorillonite from a borehole seal (or from a buffer surrounding waste canisters) is difficult because a mathematical description of the paste-to-sol transition is still lacking. Therefore, estimates presented in subsection 6.3 of [12] are based simply on extrapolation (in time) from laboratory experiments simulating behaviour in HSR, and suggest that a significant proportion of the bentonite in the borehole seal could be lost by erosion if dilute groundwaters persist for long periods of time (of order thousands of years).

In reality, we believe these scaled-up estimates are likely to be pessimistic. For example, the fracture in the laboratory experiment is smooth and planar, whereas real fractures have variable apertures and rough surfaces that may trap the sol. We note that SKB is planning to put more effort into understanding factors that may reduce bentonite erosion in dilute groundwater. Some work has also been recently initiated on the potential for natural analogues to provide more information on bentonite erosion. Output from these studies will also be valuable in the context of borehole sealing.

At the current generic stage in the GDF siting process, the present day groundwater conditions at GDF depth are uncertain, as is the future evolution of the groundwater chemistry. However, an initial estimate of the likely ranges of groundwater composition at GDF depth in geological environments of potential relevance to GDF siting (Table 2-2) indicates that, under current climatic conditions in the UK, groundwaters with dissolved solid concentrations below the CCC are unlikely. Such dilute groundwaters at GDF depth might occur in HSR during future periods of glaciation; site-specific information would be required to understand if such deep intrusions of dilute groundwater had occurred during past glaciations.

8.3 Homogenisation of bentonite

8.3.1 Review of the current knowledge base

The three stages of the bentonite swelling and homogenization process (water saturation, swelling until pore pressure equalization and creep) were described in subsection 8.1. The homogenization process can to some extent be modelled but there are still large uncertainties in these models, particularly in the prediction of homogenization by long-term creep. Consequently, in the Phase 2 borehole sealing project, emphasis has been placed on acquiring and reviewing experimental data to determine the extent of homogenization that might be expected in a borehole.

Bentonite homogenization has been investigated in laboratory experiments with many different test arrangements (see Section 4 of [12] and references therein). Experiments where swelling occurred solely in the radial direction are reported in [36], and were performed with cylindrical bentonite samples in test cells of diameter 50 mm or 100 mm. The variable in each series of tests was the width of the initial gap between the bentonite sample and the wall of the test cell.
This ranged between approximately 3 mm and 10 mm, similar to the gap widths of relevance to placing bentonite blocks in boreholes; see subsection 5.2.3. In the tests, bentonite samples with initial densities of approximately 1,660 kg/m$^3$ and known radii were placed in the test cells and allowed to saturate and swell radially. After completion of swelling, the cells were dismantled and water content and density distribution in the direction of swelling (i.e. radially) was determined$^{21}$. The densities of the subsamples are plotted in Figure 8-1; the position on the horizontal axis is the ratio of the position from which the subsample was taken (measured as the radial distance from the axis of the sample) to the radius of the bentonite sample at the end of the swelling test.

![Figure 8-1](image)

**Figure 8-1** Distribution of dry density over the radius. Results from some tests with solely radial swelling. Reproduced from [36]. See footnote for further details

The results in Figure 8-1 show that extensive bentonite homogenization has occurred in these short-timescale (few months duration) tests. The gaps between bentonite and cell walls have been closed, and in the experiments the density of the bentonite at the position of the cell wall had increased (relative to the original void) to between 950 and 1,000 kg/m$^3$ relative to approximately 1,250 kg/m$^3$ at the axis of the sample. The experiments demonstrate that initial gaps of a few tens of mm in a 100 mm diameter borehole will close on a short timescale in the presence of a free water supply and sufficient bentonite. Three larger-scale experiments were also undertaken in the second stage of the laboratory programme to simulate the resaturation of bentonite seals in a borehole. These experiments, described in subsection 7.4, measured the development of swelling pressure in bentonite seals formed from pellets and blocks and determined the hydraulic conductivity and heterogeneity of the bentonite seal after resaturation is complete. Extensive homogenisation occurred but, like the experiments described above, some density gradient remained between the axis and perimeter of the ‘borehole’. This heterogeneity was considered to give rise to only a modest

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$^{21}$ The labels in Figure 8-1 show the sample name (R11-19, R11-20 or HR-Ro1) and the percentage swelling of the sample by the end of the test (e.g. 42%). Locations ‘15mm’, ‘30mm’, ‘45mm’ and 60 mm in sample HR-Ro1 refer to the height above the base of the 80 mm high sample at which radial swelling pressure was measured and the reported dry densities were determined in 1 cm thick sections centered at these heights. The initial diameter of samples R11-19 and R11-20 was 43.8 mm; that of HR-Ro1 was 81 mm.
(less than a factor of three) variation in hydraulic conductivity across the seal, which is not considered to be significant.

The experiments described above provide information on the saturation and swelling phases of the bentonite homogenization process, as all the tests have been run to water saturation and pore pressure equalization. Longer-term tests to investigate creep are being performed as part of the SKB programme. So far, the tests indicate very little creep has occurred. For borehole sealing, the effect of any longer-term creep would be to increase homogenization and is likely to improve the sealing performance. However, the experiments described above (e.g. in Figure 7-10 and Figure 8-1) demonstrate that substantial homogenization is already achieved on short-timescales.

Interestingly, the review of analogue evidence of relevance to borehole sealing [14] noted evidence for widespread creep throughout a natural bentonite from the Kato Moni site in northern Cyprus. Here, lithostatic loads have induced creep in the bentonite, but it is most marked where significant grain-size differences exist (e.g. where slightly coarser laminae exist) or along the boundaries of natural bentonite micro-pellets. This would appear to be the case despite high friction angles and high (1,600-2,000 kg/m²) bentonite densities, both properties which would be expected to mitigate creep.

### 8.4 Chemical alteration processes in bentonite

Chemical processes that could cause mineralogical alteration to the swelling clay minerals in bentonite are discussed in Section 4 of [12]. In subsection 5.2.2 of this report, we highlight that the swelling mineral of interest in bentonite is montmorillonite, a member of the smectite group of minerals. In this subsection, we have generalised the discussion and refer to ‘smectite’ where the alteration mechanism is appropriate to the smectite group of minerals rather than specifically to one mineral such as montmorillonite.

#### 8.4.1 Illitization

Illitization of smectite has been considered as a potential process that could occur in bentonite, and which could be deleterious to swelling properties. Illite is a common K-bearing, aluminous, non-swelling 2:1 layer-silicate with a typical simplified half unit cell composition of K₀.₅₋₀.₇₅ Al₂ Si₃₂₅₋₃₇ Al₆₋₇·₅ O₁₀(OH)₂ that generally has a higher layer charge compared with montmorillonite and interlayer K⁺ essentially fixed in position.

Observations of illitization in nature and the results of experimental and modelling studies are summarised in [12, 14]. It was concluded in [12] that smectite present in borehole seals is very unlikely to undergo significant illitization under performance assessment timescales (up to 1 Ma) in either HSR or LSSR environments. The main factor is the low temperature likely to be encountered in boreholes in the UK at 2,000m depth; a maximum ambient temperature of approximately 90°C, with an average temperature at this depth likely to be approximately 60°C (see subsection 3.3.5 of [1]). Other natural analogue data also support this assertion (e.g. subsection 2.3 of [14]). Minor illitization, if it did occur, is unlikely to result in loss of sealing capacity. Further information is presented in subsection 5.1 of [12].

#### 8.4.2 Interaction of bentonite with saline groundwater

Alteration of smectite at the seal-rock interface could occur because of reaction with groundwater rich in Mg or due to groundwater compositions favouring stability of other clay minerals. This could result in smectite alteration at the seal-rock interface. The long-term stability of bentonite deposits after invasion by seawater during their geological history is reported in [14]; no mineralogical changes were observed. Bentonite present in boreholes seals could, in theory, undergo a degree of alteration to Mg-rich smectite or other Mg-rich clays over many thousands of years (possibly over a spatial scale of a few centimetres), depending on intruding water compositions and rates of advective flow (if present) and diffusion. If newly-formed Mg-rich minerals do not have inner-crystalline swelling, there could be a degree of ‘stiffening’ of bentonite borehole seals, but it seems rather unlikely that this process would be
deleterious in terms of sealing, as the precipitation of new minerals is likely to fill voids or porespace rather than result in porosity increase.

In summary, some potential alteration products are non-swelling, but it appears unlikely that a reduction in overall swelling pressure would result in seal failure. Porosity may decrease in the alteration zone.

8.4.3 Bentonite alteration by alkaline fluids

Most studies on bentonite stability in the presence of alkaline fluids have focused on the interaction of bentonite with hyperalkaline fluids associated with concrete or cementitious materials, especially those containing OPC. Evidence for the nature and spatial extent of reactions have come from natural analogue, laboratory experimental and modelling studies. Typically, studies of cement-clay and cement-bentonite interactions suggest the development of an alteration zone that includes cement solids, cement alteration products (especially carbonate) and silicate-rich rock alteration products, especially zeolites/feldspathoids and clays. Reactive transport models and natural analogue observations suggest that alteration may be relatively restricted to a scale of centimetres to a few tens of centimetres, with an associated porosity decrease occurring over tens of thousands of years.

In conclusion, reaction between cement and bentonite is likely to occur in a narrow zone at the top and bottom of bentonite seals that are in contact with cementitious materials forming support elements. This could result in a partial decrease in the swelling capacity of the bentonite as an alteration zone develops between the two materials, probably a few centimetres in thickness. This would not affect the performance of the overall borehole seal. If the support elements were constructed with low-alkali cement blends rather than Portland cement, alteration may be less extensive or even very limited.

8.4.4 Iron-bentonite interactions

Iron-bentonite interactions, which may result in reduction in swelling, are very unlikely to be significant in the absence of large sources of iron such as corroding steel objects. If steel casing were to be left in the borehole, there could be a degree of iron-bentonite interaction. As with the interaction of bentonite with alkaline solutions, evidence for the nature and spatial extent of reactions have come from natural analogue, laboratory experimental and modelling studies. Depending on the composition of intruding groundwater and the corrosion behaviour of iron materials, smectite may be replaced to some degree with non-swelling clay minerals at the metal-clay interface, potentially leading to a reduction in swelling pressure. Based on available experimental data and modelling studies, it appears to be unlikely that iron-bentonite interactions and the replacement of smectite with an iron-rich swelling clay (e.g. iron-rich saponite) or non-swelling clay mineral will lead to large increases in porosity or permeability of the bentonite, although some experimental data suggest that micro-cracking and possibly shrinkage could occur in the iron-rich alteration zone at the clay-metal interface.

8.4.5 Bentonite cementation due to silica precipitation

Bentonite cementation in borehole seals due to silica precipitation resulting from illitization reactions appears unlikely in the absence of proximity to heat-generating wastes over timescales relevant to performance assessment (order of 1 Ma). Depending on host rock groundwater/porewater composition and chemical disequilibria between it and the bentonite porewater, some minerals may precipitate at the seal-rock interface, but this is likely to result in porosity reduction rather than a loss in bentonite mass.
9 Aspects of borehole sealing in evaporites

9.1 Introduction

More than any other geological environment, understanding of the long-term performance of borehole seals in halite should take account of the movement (or ‘creep’) of the rock around the borehole. This movement of the halite around the seal could mitigate the effects of any shrinkage in the seal and, for this reason, the Phase 1 borehole sealing report concluded that borehole seals in halite could be formed either from natural evaporite minerals or from salt-saturated cements. The report also concluded that the composition of evaporite seals (either formed from natural evaporite minerals or from salt-saturated cements) would depend on the site evaporite mineralogy and, for this reason, recommended that RDD to design such seals should be left until the site-specific stage of the GDF siting programme.

Two aspects of borehole sealing in halite formations have been addressed in the Phase 2 borehole sealing project because they are generic issues.

Protection of borehole seals in halite against dissolution. A review was undertaken into experience and practice in sealing boreholes at the upper boundary (and also potentially, lower boundary) of halite formations.

Long-term performance of salt cement. Salt cements and salt concretes22 are used extensively in the oil and gas industries for sealing boreholes in subterranean evaporite formations. A review of the evidence base on the longevity of salt-saturated cements was undertaken; any areas for future RDD were identified.

9.2 Protection of borehole seals in halite against dissolution

9.2.1 Scenarios

Two distinct situations should be considered for a site investigation borehole drilled into a bedded halite formation.

Fully penetrating borehole. In this situation, the borehole fully penetrates the bedded halite formation. That is, it is drilled through the halite formation into the underlying rocks.

Partially penetrating borehole. In this situation, the borehole is drilled into the bedded halite formation but does not reach the rocks underlying the halite. That is, it does not penetrate the full thickness of the bedded halite formation.

In each situation, RWM’s base case assumption is that the borehole casing has been removed prior to sealing. We recognise that this may not be practicable in all situations, and therefore in the discussion below also consider the case where some or all casing remains in the borehole.

In the case of a fully penetrating borehole, the environmental head difference between the formations overlying and underlying the halite provides the potential for groundwater to flow through the borehole. This groundwater is unlikely to be halite-saturated; it originates from the formations overlying or underlying the halite. If such groundwater flows through an uncased fully penetrating borehole in halite, it would immediately start to dissolve the halite surrounding the borehole. Dissolution of the halite surrounding the borehole would also be the eventual outcome

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22 Salt cement and salt concrete (cement plus aggregate) are used here as terms for cement and concrete mixtures where salts such as NaCl or MgCl have been added to the principal cement components and/or salt water / brine has been used to make the cement.
if the borehole were cased, as the casing will corrode and degrade within the timescale addressed by the ESC. Most importantly, in either situation this would be a continuing process and, if sufficiently extensive, dissolution would be detrimental to the performance of the geological barrier.

The actual flow rate through a fully penetrating borehole in halite would depend on the head difference between the overlying and underlying formations, the permeability of the borehole and the transmissivity of the overlying and underlying formations. The groundwater flows could be substantial if the overlying and underlying formations are of at least moderate transmissivity. In these circumstances, the seal material in the borehole will need to have low permeability at the time of emplacement in order to prevent water flow through the borehole.

In the case of a partially penetrating borehole, there is no potential for groundwater to flow through the borehole; it does not cross-connect transmissive horizons and the halite surrounding it will be of extremely low permeability. The borehole will fill with groundwater draining from the overlying formation. Because the groundwater is not saturated with halite it will initially dissolve halite from the walls of an uncased borehole. However, because the groundwater in the borehole is stagnant it will quickly become halite-saturated and further dissolution will cease. In the medium term, the uncased borehole will seal due to convergence (‘creep’) of the halite surrounding the borehole.

The discussion above highlights that a borehole seal in a fully penetrating borehole through halite, whether cased or un-cased, will need to have low permeability at the time of emplacement, whereas there is no such requirement for a partially penetrating borehole. Materials that are used to seal openings in salt and which have low permeability at the time of seal emplacement include salt concrete and asphalt. For example, both of these materials are proposed for use in shaft seals at WIPP (see subsection 3.3.3 of [13]), as discussed below.

9.2.2 Information from repository shaft seals

The sealing of repository shafts will have similarities to the sealing of un-cased boreholes, albeit on a larger scale. The design of shaft seals for WIPP is discussed in subsection 3.3.3 of [13]; the shafts will be sealed using crushed halite along most of their length within the Salado bedded salt formation. In addition, three concrete-asphalt ‘waterstop’ (a variety of seal) components will also be located within the seal through the Salado Formation to limit fluid transport. These components comprise three elements: an upper salt concrete plug, a central asphalt waterstop, and a lower salt concrete plug. The purpose of the salt concrete-asphalt components is to provide a low permeability barrier that protects the crushed salt until it has consolidated as a result of creep of the salt around the borehole and provides a long-lived low permeability seal.

In the German shaft seal design for Gorleben, the shaft seals will consist of three short-term sealing elements that maintain low permeability until the compaction of the long-term sealing element (crushed salt) has been achieved. The short-term sealing elements are based on Sorel concrete in the lowest element, salt concrete in the middle element and bentonite in the upper or top element. Salt concrete, based on calcium cement, is more stable in an environment with NaCl-rich brines, while Sorel concrete, based on magnesium cement, is more stable in potash rock environments with MgCl₂-rich brines. The use of different materials at different levels and in different places reflects the variation in lithology and hydrochemistry with depth. The short-term sealing elements are all positioned in an anhydrite layer in the rock salt, to prevent any groundwater flow in the anhydrite layer entering the borehole.

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23 The Sorel cement is a mixture of magnesium oxide and magnesium chloride (brine), generally in the weight ratio of 2.5–3.5 parts MgO to one part MgCl₂. The aggregate component, as in salt concrete, is the crushed evaporite rock (generally halite).
9.2.3 Information from sealing cased boreholes

The WIPP performance assessment (PA) considers long-term releases to the ground surface or groundwater in units overlying the evaporite host rock through the sealed shaft (undisturbed performance) and through plugged and abandoned boreholes (disturbed performance).

Future borehole seals at WIPP are assumed to have properties consistent with current borehole sealing practice in the area surrounding the WIPP. Such boreholes have salt concrete plugs emplaced within the borehole casing at various locations to limit fluid flow in the cased borehole. How sealing is to be achieved varies depending on the formation in which the seal is to be placed. Either a complete salt concrete seal is placed throughout the halite horizon, or shorter salt concrete seals are used to isolate particular, more permeable horizons. Borehole seal scenarios developed by the WIPP programme consider the possibility of the borehole seal failing because of corrosion and eventual physical collapse of the borehole casing.

Guidelines from the German Mining Authorities regarding the backfilling of boreholes in salt are presented in \[37\]. The guidance does not specify a specific material; seals are to be provided by filling ‘with suitable cement or with other suitable solids, if appropriate in conjunction with mechanical seals’. Schematics of sealing approaches are provided in the guidance, and show the use of such materials for sealing both cased and un-cased sections of borehole. Where sealing behind casing is required, the guidance identifies perforation of casing and subsequent pressure cementation as the approach.

9.2.4 Recommendations

The literature review \[13\] found that designs for shaft seals in the US and Germany incorporate materials to provide low permeability at the time of emplacement and in the short term until the crushed salt, which forms the long-term seal, has consolidated and achieved low permeability. Salt concrete, asphalt and bentonite were identified. However, no examples have been found of the use of asphalt or bentonite to seal boreholes in evaporites; in contrast, extensive use is made of salt concrete in borehole seals.

For the purposes of sealing a fully penetrating borehole in bedded halite formations, we recommend that an appropriate concrete formulation, such as salt concrete or Sorel concrete, be used at the upper and lower boundaries of the halite formation to protect against halite dissolution and/or short-term groundwater flow through the borehole. The choice of cement formulation would depend on the mineralogy of the evaporite in contact with the borehole. The central element of the borehole seal could be formed from crushed salt or other evaporite minerals (depending on the mineralogy of the evaporite in contact with the borehole) or by a suitable cement formulation. The seal therefore has two components, with short-term and long-term functions. The cementitious component provides low permeability in the short-term (tens to hundreds of years) and, for an uncased borehole where convergence of halite around the borehole will occur, low permeability also in the longer-term. The salt component of the seal consolidates to form a seal in the long-term (timescales of order a hundreds of years and longer).

In the case of a partially penetrating borehole in bedded halite formations, it is not essential to place a cement seal at the upper surface of the halite. If a cement seal is not to be used, it will be necessary through scenario analysis to demonstrate that there would be no adverse outcomes from its omission. In practice, it is likely to be more straightforward to include the cement seal rather than to attempt to justify its omission, and this is the recommendation from the project.

9.3 Long-term performance of salt cement and salt concrete

Discussion of salt concrete in reference \[13\] is organised into two main sections dealing separately with the use and emplacement of salt concrete in boreholes through evaporites, and the long-term performance of salt concrete when used to seal boreholes and other openings (e.g. excavation tunnels) in evaporites. For use and emplacement, the report principally uses
literature from the oil and gas industry and other resource exploitation industries, such as solution mining and underground gas storage, where there is considerable experience in the development and application of salt concrete.

However, the main issue of interest to the project is the long-term performance of salt concrete, and there is little research relevant to this issue in the resource-exploitation literature. Further, the timescales of interest to radioactive waste management programmes regarding performance are far in excess of the timescales of actual experience of using salt concrete. Therefore, with regard to long-term performance, reference [13] focused on the predictive modelling undertaken for waste management programmes concerned with a geological disposal facility in evaporites (USA and Germany). The review of this literature concluded that salt concrete can be expected to provide adequate performance with regard to sealing boreholes in evaporites. Predicted failure of seals in the USA waste management programme is generally related to corrosion of casing in an aggressive chemical environment – a situation that does not apply to the RWM concept, where the base case assumption is that casing will be removed before borehole seals are placed. Even in such cases, the WIPP PA concludes that the pathway is not of radiological significance. See discussion in subsections 3.3.4 to 3.3.6 of [13].

Research and experience demonstrate the generic conclusion that boreholes in evaporites can be sealed using a combination of appropriate cementitious formulations and natural minerals. The exact composition of borehole seals in evaporite sequences will depend on the site evaporite mineralogy; selection of materials for such seals should be left until the site-specific stage of the GDF siting programme.

An appropriate concrete formulation, such as salt concrete or Sorel concrete, should be used at the upper and lower boundaries of the halite GDF host rock to protect a borehole seal formed from halite until it has consolidated and achieved low permeability.
10  Impact of gas

10.1  Introduction

So far, the work described in this report has considered borehole sealing in the context of the groundwater pathway only. Task 14 within the Phase 2 borehole sealing project considered the possibility of gas migrating to a decommissioned site investigation borehole, and then through a borehole seal formed from bentonite.

The first part of the report from Task 14 [11] presented information on gas generation and gas migration relevant to borehole sealing and concluded with an overview of gas migration in the illustrative geological environments being considered by RWM. This work is summarised in subsection 10.2. The second part of the report then considered a number of key questions concerning gas migration and sealed site investigation boreholes.

Could the presence of a sealed site investigation borehole affect the gas pathway?

How might gas flow through the potential pathways associated with a decommissioned borehole: (i) through the borehole seal itself, (ii) through the annular gap that might form between the seal and the surrounding rock, or (iii) through a damaged zone of rock (the Borehole Damage Zone, or BDZ), which forms immediately adjacent to the borehole?

Could the presence of gas damage a seal in a decommissioned site investigation borehole?

The results are summarised in subsections 10.3 to 10.5, with overall conclusions being presented in subsection 10.6.

10.2  Gas generation and migration issues relevant to borehole sealing

10.2.1  Gas generation processes

The processes that will generate either large volumes of bulk gases or significant quantities of radioactive gases in a GDF are considered to be:

- corrosion of metals (this includes the release of carbon-14 from neutron-irradiated metals as they corrode);
- radiolysis of porewater and some organic materials; and
- microbial degradation of organic materials.

The bulk gases will comprise hydrogen, which could be generated by corrosion of metals as well as radiolysis of water in grouts and organic materials, and methane and carbon dioxide, which could be generated by microbial degradation of organic materials, mainly in LLW and ILW. Although most of the gas will be non-radioactive, a tiny fraction will be radioactive. The radioactive gases are likely to include tritiated hydrogen (with one atom of hydrogen in the molecule replaced by an atom of the radioactive isotope, hydrogen-3), radioactive methane, carbon monoxide and carbon dioxide (with the carbon atom in the respective molecules replaced by an atom of the radioactive isotope, carbon-14), and radon (radon-222). Although the quantities of these radioactive gases will be small, their significance has to be considered because of their radioactivity.

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24 In this report, we only consider placement of borehole seals directly against the rock. In these circumstances, the only annulus potentially present is that between the seal and the rock immediately surrounding the borehole.
10.2.2 Gas flow and transport mechanisms

The principal flow and transport mechanisms, which will determine how gases migrate from a GDF, are:

- fluid (i.e. both gas and groundwater) flow in response to pressure gradients;
- buoyancy-driven flow;
- dissolution into the groundwater;
- diffusion; and
- dispersion, and fingering, caused by formation heterogeneities.

Ongoing gas generation within a GDF will increase the pressure there, creating a pressure gradient that will drive fluid flow away from the GDF. This would be an important mechanism in a LSSR (e.g. mudrock), but less so in other environments where the host rock has fractures.

Buoyancy-driven flow is caused by the lower density of a gas phase compared to the groundwater in the rock. In a HSR, buoyancy would cause the gas to migrate upwards until either it reaches the surface or it encounters a low-permeability formation, where it would accumulate at high points. In settings where the gas encounters a low-permeability formation, the presence of open faults or fracture zones could allow onward passage of the gas.

If the gases come into contact with sufficient water as they migrate, then the gases will dissolve into the water. The significance of this mechanism depends on the velocity of the gas phase, and the contact area between the gas phase and the water. It could be an important mechanism in a LSSR, where the host rock has a relatively large porosity (and hence a relatively large potential for gas dissolution) and the gas will migrate only slowly. It would be less important in a HSR, where the porosity will be small and the gas will migrate quickly. However, even in the latter geological environment, pockets of trapped gas will accumulate in some places, and around these pockets dissolution will occur.

Lastly, heterogeneities within the permeable geosphere (particularly unsealed faults and fracture zones) could cause the gas pathway either to spread out or to be focused as it migrates upwards.

10.2.3 Gas migration pathways and barriers

In general terms, gas could migrate through the following pathways: the rock matrix; fractures and faults; and/or man-made features including the GDF, the Excavation Disturbed Zone (EDZ) around the GDF and boreholes.

LSSR of potential relevance as a GDF host rock are mechanically weak and cannot sustain open fractures. Therefore, a gas phase will have to migrate through the matrix of these sedimentary rocks. This would be a slow process, which would give volatile radionuclides time to decay away. In other types of rocks, open fractures are present and these will allow the flow of gas through the geosphere, particularly if they are found in low-permeability layers which otherwise would act as seals.

There are many mechanisms that could trap gases migrating through the geosphere. Several trapping mechanisms are simply the result of the geometry of the geological sequence (see Figure 10-1).

25 Fingering can also be caused by the contrast in mobility between the gas and the groundwater. (The mobility of a fluid is defined as its relative permeability divided by its viscosity.) This ‘viscous’ fingering will occur when the surface tension acting across the interface between the gas phase and the groundwater (i.e. the capillary pressure) is small compared to the viscous forces, and therefore is more likely to be observed in porous media with fracture-dominated permeability.
Figure 10-1  Schematic showing the two basic examples of structural traps (i.e. the anticline trap and the fault trap), as well as a stratigraphic trap

10.2.4 Gas migration in illustrative geological environments

As a precursor to considering whether site investigation boreholes could affect the gas pathway through the geosphere, this subsection summarises the main features of gas migration in geological environments being considered by RWM. See Section 2.

HSR to surface

HSR, which may be igneous, metamorphic or older sedimentary rocks, have a low matrix porosity and low permeability, with the majority of any groundwater movement confined to fractures within the rock mass. In this environment, groundwater would flow through the fractures, with negligible flow through the rock matrix between them. A gas phase would be able to move easily upwards from the GDF through the fracture zones to the ground surface.

HSR under Sedimentary Cover

HSR might be overlain by a sedimentary sequence. In this environment, a gas phase would move upwards from the GDF through the host rock until it comes to the overlying formation. If the sedimentary cover rock has high permeability, then the gas could continue to move upwards, but if it has low permeability with a high gas entry pressure, then the gas would accumulate beneath this formation, and is likely to spread out. What happens to the gas next will depend on site-specific features.

If the low permeability formation acts as a cap rock, then the gas could be trapped for a long time.

If a transmissive feature (e.g. an open fault, which allows more vertical movement) is present, then that could provide a more focused pathway for the gas to migrate upwards to the ground surface.

Lastly, if an aquifer is present, then the gas might dissolve in its groundwater, although it might de-gas at lower pressures in the near-surface region.
LSSR

LSSR are mechanically weak and cannot sustain open fractures. The main differences compared to gas migration in HSR are:

- the hydraulic conductivity of the host rock – the hydraulic conductivity will be lower in LSSR, and therefore larger pressures will be needed for the same flow;
- the size of the pores in the host rock – in a LSSR, the pores will be very small, and so a large capillary pressure\(^26\) will be needed before the gas phase can start to migrate into the surrounding host rock;
- the porosity of the host rock – the porosity is likely to be higher in a LSSR, and therefore there will be more groundwater present into which the gases can dissolve.

As a consequence of these differences: resaturation times will be long; much higher pressures will be required before a gas phase from the GDF can migrate into the surrounding rock, and; the gas will move only slowly through the host rock. Calculations of the time to cross a 50m thick layer of LSSR are typically several thousand years [38, 39].

Because of the low hydraulic conductivity of the host rock, it may not be possible for a gas phase to migrate away from the GDF quickly enough to relieve the build-up of gas pressure. In this case, micro-fissures might form in the rock and relieve the gas pressure before sealing again. Gas also might migrate through the more permeable EDZ surrounding the excavation, and this would have to be considered when developing the disposal concept.

Evaporite

An example of an evaporite is bedded halite (or rock salt), which might lie in a sequence that contains other low permeability sediments. The illustrative design for a GDF in an evaporite assumes that the packages of ILW / LLW will be emplaced in open vaults. At first, the rock salt will be gastight. The wastes (which will contain some pore water at the time of their emplacement) will generate gas, and therefore the gas pressure within a vault will increase. Concurrently with gas production, rock convergence will occur.

Understanding from the German radioactive waste management programme is that if the gas pressure within a vault were to approach the minimum principal stress in the host rock (i.e. approximately twice the hydrostatic pressure), then either the salt would become permeable or the void space within the GDF would increase. The first process (‘gas infiltration’) is considered to be the more likely to occur, and would result in a limited flow of gas into the salt. A zone of gas-pressurised rock would develop (i.e. gas will be stored in the salt matrix, in the immediate vicinity of the GDF, which is similar to many observations that have been made in the field).

10.3 Could the presence of a sealed site investigation borehole affect the gas pathway?

We conclude in Section 5.2 of [11] that any groundwater flow that takes place through the sealed borehole will not affect the gas pathway; that is, the gas phase will not be ‘captured’ by the borehole. For the range of potential host rocks considered by RWM in the 2010 generic Disposal System Safety Case, we then identified that a decommissioned site investigation borehole can only become an important part of the gas pathway if:

- the host rock is a higher strength rock (HSR), and
- the host rock is overlain by a lower strength sedimentary rock (LSSR), and
- a gas phase migrates away from the GDF through fractures in the HSR and accumulates

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\(^{26}\) Capillary pressure is the difference in pressure across the interface between two immiscible fluids. In this context, it is the difference in pressure between the gas phase and the liquid phase. The Young-Laplace equation relates the capillary pressure to the inverse of the pore size.
beneath overlying low permeability strata in the vicinity of the sealed borehole, and gas is able to migrate through or around the borehole seal.

The radiological consequences of the migration of long-lived radionuclides such as carbon-14 in the gas phase depend on the area over which the gas is released in the biosphere. Radiological consequences are potentially highest if gas release is focused over a limited area. Consequently, gas pathways that have the potential to focus gas release in the biosphere are potentially detrimental. The radiological consequence of release of radioactive gases to the biosphere is also dependent on the timing of the radionuclide release relative the half life of the radionuclide. Pathways that circumvent barriers to gas migration in the geosphere have the potential to increase radiological consequences.

Flow of gas through a decommissioned site investigation borehole could contribute to both focusing of gas release in the biosphere and earlier release of gas to the biosphere in the case of the scenario given above. Gas flow through the borehole is therefore not desirable, and decommissioned boreholes should therefore be designed to prevent or minimise gas migration in the case where the borehole intersects LSSR in a region where accumulation of GDF-derived gas is possible. In all other situations, a decommissioned site investigation borehole (however sealed) will not affect gas movement from a GDF to any significant extent. Then, no further consideration is needed.

10.4 How might gas flow through the potential pathways associated with a decommissioned borehole?

Reference [11] summarises previous work that shows bentonite has high gas permeability until it is water-saturated. The report also shows the potential for gas to migrate through any annular gap that might form between the bentonite seal and the rock, and through the BDZ that forms in the rock immediately adjacent to the borehole. However, once a borehole seal formed from bentonite has resaturated, it will form a high-quality seal against gas flow (i.e. it will form a seal with a high gas entry pressure, which will prevent gas migration). The annular gap between the bentonite and the surrounding rock is likely to be closed because of the swelling pressure exerted by the bentonite seal. Where the borehole is constructed in LSSR, the BDZ is likely to be totally or partially healed as a result of natural long-term creep of the rock around the sealed borehole.

The timescale on which the gas phase could migrate to the location of the borehole depends principally on the GDF design and the host rock permeability27. (Note that the term ‘permeability’ is used in this section of the report in place of ‘hydraulic conductivity’ because the section is concerned with flow of gas and water through the rock.) If the GDF were situated in a relatively permeable HSR (e.g. permeability of the order of $10^{-16} \text{ m}^2$), then the gas phase could migrate from the GDF to the location of the borehole seal in a few years after GDF closure. Decommissioned boreholes should therefore be designed to prevent or minimise gas migration in the case where the borehole intersects LSSR in a region where accumulation of GDF-derived gas is possible. A requirement is that the bentonite seal re-saturates before the gas phase has migrated to the location of the borehole.

As shown from the results of the Bentonite Rock Interaction Experiment at the Äspö Hard Rock Laboratory, resaturation of a borehole seal formed from high density bentonite blocks is not likely to be achieved on a timescale of a few years. If bentonite blocks are to be used as the borehole sealing material, it would be necessary to decommission (seal) the borehole at a much earlier time than the GDF is closed. Alternatively, assuming that the required standard of sealing against groundwater flow could be achieved, bentonite pellets could be used as the sealing material. The timescale for resaturation of bentonite pellets is expected to be much shorter than

27 As demonstrated in reference [11], the potential for a gas phase to form is influenced by the nature of the wastes disposed and on the flow of groundwater through the disposal vault.
for high density bentonite blocks, as demonstrated by the experimental results presented in subsection 7.4.

10.5 Could the presence of gas damage a seal in a decommissioned site investigation borehole?

If gas were to accumulate beneath a LSSR at the location of a decommissioned site investigation borehole, then it could exert a load on a borehole seal. The load (or excess gas pressure) would depend on the geometry of the features trapping the gas, and could be any value up to the gas entry pressure of the features; that is, up to several megapascals. Therefore, depending on site-specific details, a borehole seal may have to be designed to withstand loads of this magnitude.

As a seal manufactured from bentonite re-saturates, its bentonite component will swell and as a result the seal itself will develop a swelling pressure. The seal's integrity should be assured provided that the sum of its swelling pressure and pore pressure exceeds the load applied by the gas phase. This is likely to be achievable in most circumstances, but may not be achievable where: the thickness of the accumulated gas phase approaches the gas entry pressure for the LSSR; the seal is located in contact with more saline groundwater, and; the rock is weak and prone to breakout at large depths. The most appropriate site characterisation strategy may be to avoid locating boreholes in such areas. Should this not be possible, consideration should be given to the use of bridge plugs near the base of the LSSR. Bridge plugs could be used to more effectively confine the bentonite seal and accelerate the establishment of its properties; they could also resist gas pressure and, potentially, gas flow.

10.6 Conclusions

This section of the report identifies the one scenario where a decommissioned site investigation borehole can become an important part of the gas pathway; where the borehole intersects LSSR in a region where accumulation of GDF-derived gas is possible\(^{28}\). For this scenario, flow of gas through a decommissioned site investigation borehole could contribute to both focusing of gas release in the biosphere and earlier release of gas to the biosphere, and is therefore not desirable. The decommissioned borehole should therefore be designed to prevent or minimise gas migration to prevent this scenario occurring. In all other situations, a decommissioned site investigation borehole (however sealed) will not affect gas movement from a GDF to any significant extent. No further consideration is needed.

The issues concerned with designing a bentonite seal that will prevent gas migration through or around the decommissioned borehole are presented. An important issue is that the bentonite seal must fully re-saturate before the gas phase has migrated to the location of the borehole; this will influence the choice of the form of bentonite (high density block, pellet or slurry) selected for the seal.

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Gas migration through a sealed site investigation borehole is a potential concern only where the borehole intersects lower permeability cover rocks in a region where accumulation of GDF-derived gas is possible. In this case, the requirement is that the bentonite seal must fully re-saturate before the gas phase has migrated to the location of the borehole. This will influence the choice of the form of bentonite (high density block, pellet or slurry) selected for the seal.

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\(^{28}\) A particular example of this scenario might have an anticline structure, with the LSSR overlying more permeable rocks. Gas could accumulate beneath the LSSR, and then potentially migrate up a nearby borehole.
11 Borehole sealing and development of a QA/QC methodology

11.1 Introduction

This section summarises the main activities associated with sealing a deep investigation borehole at the site for a potential GDF. The most important parameters for ensuring correct seal emplacement at depth are identified, and an outline Quality Assurance / Quality Control (QA/QC) methodology for borehole sealing is proposed. A more detailed description of the work undertaken is given in [7]. This section does not address the management of health and safety during the emplacement of the borehole sealing system. The Safe System of Work will be developed once the detailed design of the borehole sealing system and the method of emplacement of the various materials have been agreed.

The section is concerned with sealing actual site investigation boreholes at a potential GDF site. Assumptions regarding the design of generic site investigation boreholes that will require sealing were given in subsection 2.6. As noted in subsection 7.1, there will be limited opportunity to determine the performance of an emplaced seal in a borehole. This is one of the reasons why RWM is undertaking a phased programme of RDD into borehole sealing. Some recommendations for the future generic RDD programme are presented in subsection 13.2. By the time of sealing an actual site investigation borehole, RDD undertaken in the UK and overseas will have developed (i) confidence in the ability to place borehole seals and supports in accord with the design and (ii) understanding of the subsequent evolution of the borehole sealing system. For this reason, and in line with the approach taken for the GDF itself, there will be no requirement to monitor the evolution of the sealing system, such as monitoring the evolving swelling pressure exerted by a bentonite seal, after it has been emplaced. The measurements described in this section are of two types:

measurements needed to design the borehole sealing system (the ‘boundary conditions’ for the seal) such as the borehole diameter, its variability and the groundwater composition, and;

measurements to demonstrate that the borehole sealing system has been placed in accordance with the design, for example the depth of emplacement of materials in the borehole and the volumes of seal and support materials placed. Potentially, hydraulic conductivity could also be estimated.

These measurements are described in more detail in the remainder of this section.

The confidence referred to above will be gained through a programme of RDD into borehole sealing, of which this project is a part. Small-scale and medium-scale laboratory experiments have already been undertaken; larger-scale laboratory mock-ups and, potentially, in situ borehole experiments will be undertaken in the future. These experiments have already involved extensive monitoring of bentonite seals as they re-saturate. New technologies, such as the application of wireless sensors, may be required as part of future demonstration experiments. However, the measurements and sensor development for such demonstration experiments are not considered in this section.

11.2 Planning steps

It is important to recognise that planning for borehole sealing should start when the borehole is being designed and any long-term monitoring installations within the borehole are being considered. For example, the choice of borehole and casing sizes has a significant impact on the planning and complexity of borehole sealing. Further, it is important that records of the as-built borehole and any equipment installed in it are kept. For example:

detailed records of the installation and its design should be kept in order to facilitate removal
of any installed borehole equipment;
detailed records of the casing system should be kept in order to increase the likelihood of successful casing removal.

The design of investigation boreholes at the site of a potential GDF, and of any long-term monitoring installations placed in them, should take account of the need for subsequent borehole sealing

The main steps in the borehole sealing process are listed below.

1. Review and agree the design requirements for the borehole sealing system. This will be driven by the requirements of performance assessment, supplemented by a requirement to protect groundwater resources: see subsections 3.4 and 3.5.

2. Review geological information, borehole logs and as-built borehole specifications. The important borehole parameters from the perspective of designing and placing borehole seals and supports should be identified. The outputs from geological logging, downhole geophysical testing, borehole completion surveys, borehole hydrogeological testing and groundwater sampling and analysis should be reviewed to obtain information on these parameters. A gap analysis should be undertake at this stage to identify any additional information required to allow the design of the borehole sealing system to be finalised. Such work should then be undertaken.

3. Prepare the design specification for the borehole sealing system. Following from the development of design requirements and identification of boundary conditions, this activity will include identifying and agreeing:
   a. the locations of seals, support elements and (if appropriate) bridge plugs in the borehole. Up to three types of support elements may be required: see subsection 3.3 for details;
   b. the as-placed properties of borehole seals and supports. The required properties of seals and supports were discussed in subsections 5.2 and 5.3, and include hydraulic conductivity of the seal and settlement potential and compressive strength of support elements;
   c. the approach to emplace materials in the borehole. See Section 6 for details of potential approaches.

Note that aspects of the design, such as quantities of material to be placed, can only be finalised after the borehole has been prepared for sealing and any surveys identified from the gap analysis under (2) above have been performed.

4. Prepare the materials specifications. Borehole seals will be formed from bentonite (subsection 5.2). A range of potentially suitable materials has been identified for supports (subsection 5.3). Materials specifications suitable to achieve the as-placed design specification should be developed. For example, this will include specifying the required quality of the bentonite.

5. Identify requirements for any materials testing to answer site-specific or borehole-specific questions. For example, it may be necessary to confirm the swelling pressure and hydraulic conductivity of the bentonite or the compressive strength and pumpability of materials for supports. These tests may be undertaken in the laboratory or in boreholes at another (non-GDF) site. They will not be undertaken in the borehole to be sealed.

6. Prepare the Method Statements (MS) and Quality Assurance Programme (QAP) for installing and testing the borehole sealing system. MS will be provisional at this stage, as further information on the borehole may be obtained when it is prepared for sealing. Key
aspects of the QA/QC methodology (to be described in the QAP) will be accurate measurement and control of volumes, flows, masses and relevant properties of materials entering the borehole and accurate measurement and control of the intervals and depths over which materials are placed. The required precision of these measurements will also need to be defined. It will also be necessary to undertake some in situ and/or ex situ measurements of the placed materials to confirm the design specification has been achieved. Lastly, the MS should also include remedial measures to be undertaken if it is found that borehole seals have been incorrectly installed or do not meet the design specification.

7. Prepare the borehole for sealing. This is a key activity, and will require detailed planning. The amount of effort required may be substantial, and should not be under-estimated. Potential activities are:
   a. removal of installed equipment such as long-term monitoring systems and other downhole equipment;
   b. removal of casing, if practicable, followed by running cement bond logs to re-evaluate the standard of cementation in remaining casing and improving the standard of cementation if it has significantly degraded;
   c. reaming out sections of borehole;
   d. cleaning out the borehole to remove debris and borehole wall cake;
   e. undertaking additional borehole condition surveys as required. At a minimum, a calliper survey will be required to determine any changes to borehole dimensions that have occurred since drilling. Other surveys required will depend on the extent of borehole characterisation undertaken as part of site characterisation.

8. Review the information obtained from preparing the borehole for sealing and update aspects of the approach to borehole sealing as required. For example, revisions may be required to:
   a. locations of seals, supports and (if appropriate) bridge plugs;
   b. materials quantities, following updated calculation of the volume to be sealed, and;
   c. method statements (MS).

9. Prepare the Quality Plan (QP) and Waste Management Plan (WMP). The Quality Plan (QP) is the document used to demonstrate that all required activities associated with sealing the borehole have been undertaken, and that these activities have been undertaken in accordance with the specified MS. It can only be prepared when the locations, depth intervals and material specifications for borehole sealing have been finalised. The Waste Management Plan fulfils a similar purpose for the management of the wastes produced during borehole sealing.

10. Install and test the borehole sealing system, using the method statements and Quality Plan. The borehole sealing system should be installed according to the MS and QP. In situ and/or ex situ measurements of the emplaced materials should be undertaken as specified in the MS and QP to confirm the design specification has been achieved. The evidence should be archived appropriately.

Some aspects of the planning process are discussed in the following subsections.

### 11.3 QA/QC methodology

The application of quality to any project generally involves three stages. Firstly, identification of the parameters in the process that require control and measurement, and understanding of the required accuracy, precision and frequency of those measurements. Second, the development of a Quality Assurance Programme (QAP), which describes the management arrangements and procedures to be applied to the project. Third, the development of a Quality Plan (QP), which is used to control activities and to demonstrate that all activities have been undertaken in accordance with the requirements of the QAP. These three stages are described below.
11.3.1 Identification of parameters that require control and measurement

The most important borehole parameters from the perspective of designing and placing borehole seals and supports are:

- the diameter and variability in diameter (‘rugosity’) of the borehole;
- the spatial extent and properties of the BDZ after drilling;
- the borehole casing scheme and the integrity of the cement bond between casing and borehole wall at borehole completion;
- the depths at which geological units and features (such as fracture zones) intersect the borehole;
- the distribution of hydraulic conductivity and groundwater heads along the borehole. Together, these will define groundwater inflows and outflows to the borehole during seal emplacement and the natural groundwater flows around and through the borehole after sealing;
- groundwater compositions along the borehole, which will influence the hydraulic conductivity of bentonite seals and the chemical and physical degradation of support elements.

In particular, the borehole dimensions and the hydraulic conductivities, groundwater heads and groundwater compositions along the borehole define the boundary conditions for the emplaced seals and support elements. The relevance of these parameters to the choice of design, materials and emplacement methods for borehole seals and supports has been discussed in earlier sections of this report.

The outputs from geological logging, downhole geophysical testing, borehole completion surveys, borehole hydrogeological testing and groundwater sampling and analysis should be reviewed to obtain information on the relevant parameters. A gap analysis should be undertaken to identify any further information required before the design of the borehole sealing system is finalised. This work should then be initiated.

11.3.2 The Quality Assurance Programme

The QAP describes the management arrangements and procedures to be applied to ensure that the borehole sealing system is installed correctly and meets the design specification. A QAP for borehole sealing is likely to include the following:

- overarching policy statement on the application of quality assurance to the project;
- definition of the Quality Standards (e.g. ISO 9001 and 14001) against which all work to be undertaken will be assessed;
- applicable management procedures. These will be written company procedures applicable to the scope of supply; all work undertaken on the project should be in accordance with these management procedures;
- project-specific method statements. Method statements will be developed for specific activities, and will be approved before borehole sealing commences. Method Statements will generally incorporate risk assessments, control measures and corrective actions. From the quality perspective, they will describe all activities necessary to ensure the required level of quality is achieved;
- management, organisation and responsibilities for the project, including identification of key control and supervision positions and specific responsibilities;
- project controls. This will include aspects such as: contract specification; project change control procedures; application of Quality Plans; progress reporting, and; control of sub-contractors;
- control of measuring and testing equipment, covering aspects such as the calibration of equipment and the accreditation of testing laboratories;
waste management, which describes the arrangements for the management of solid and liquid wastes produced from borehole sealing;
non-conformance and corrective action;
training, including the provision of training records to demonstrate that all staff are suitably qualified and experienced (SQEP) to carry out the required work;
compliance of procedures with quality assurance requirements, through maintenance and storage of project records and implementation of audits undertaken by (as required) the project team, the customer and external organisations.

11.3.3 The Quality Plan

The Quality Plan is used to control activities and to demonstrate that all activities have been undertaken in accordance with the requirements of the QAP. It is in tabular form, with each required activity forming a row on the plan. The controlling document (e.g. the method statement) for each activity is specified. The responsible person for each activity is specified, together with any required witness or witnesses to the activity. The titles and locations of any documents produced from the activity are to be listed. Lastly, the Quality Plan identifies any Hold Points during the borehole sealing process, beyond which activities shall not progress without written approval from, for example, the responsible manager or client. At the end of the activity, the relevant line in the Quality Plan is signed off to confirm the activity has been completed in line with the controlling document; details of any documents produced from the activity are added. At the end of the borehole sealing process, all activities should be signed off; at this stage, the responsible manager will approve the completed Quality Plan to confirm that all work has been successfully completed.

11.4 QA/QC methodology during installation of the borehole sealing system

QA/QC applied by the oil and gas industry during sealing of site investigation boreholes was described in the Task 5 report from the project [4]. Sections 4 to 8 of that report presented illustrative methods for the emplacement of materials in boreholes by conventional pumping, coiled tube pumping, gravity emplacement and dump bailing. The report also identified the important parameters that needed to be controlled and measured, and described how this could be achieved. Additional information on methods and QA/QC for placing sealing materials in boreholes by pumping, gravity emplacement and dump bailing is given in Section 6 of [7].

The oil and gas industry has extensive experience of placing cementitious materials in boreholes by pumping, and the methodologies and approaches to ensuring quality for placing pumpable materials in boreholes will provide the framework for similar activities at the site of a potential GDF.

The most important aspects for the QA/QC related to the correct emplacement of the borehole sealing system at depth are:

- material compositions (e.g. water content, density, particle size distribution, component proportions) need to be controlled and measured before they are placed in the borehole;
- volumes of materials placed in the borehole should be measured at surface through use of flow meters and pump strokes, or by accurately measuring the volumes of dump bailers;
- depths of placed materials should be determined by dipping/tagging the upper surface of the material. An understanding of the accuracy and precision of the measurement, and how this varies with increasing depth, is required;
- seals and supports need to be sufficiently long to limit the effect of uncertainty in depth measurement in deep boreholes.

Dump bailers are recommended for placing bentonite pellets and blocks, and some materials for support elements, in boreholes. Dump bailers provide a means of accurately placing known
amounts of materials at known depth in the borehole. Their use will therefore simplify some of the QA/QC measurements to be undertaken at the borehole top, in particular volume and depth measurements. The simplicity of the dump bailer emplacement technique will also build confidence that materials have been installed in accordance with design.

11.5 QA/QC methodology during testing of the borehole sealing system

It was noted in [7] that most QA/QC activities applied to date in borehole sealing take place at the ground surface. This is in part because of the techniques used to seal the borehole, and in part because of the complexity of making down-hole measurements, some of which have the potential to damage the seal and compromise its sealing performance. In this subsection, depth determination and hydraulic testing are identified as measurements that could be made downhole on borehole seals and support elements. Other downhole measurements, such as recording strains (displacements) or mechanical pressures, are not required as previous RDD will have built the necessary level of confidence in the subsequent evolution of the seal properties.

11.5.1 Depth of placed materials

Depths of placed materials will be determined by tagging or measurement. Tagging would be undertaken using a tubing string or drill pipe; measurement would be undertaken using a wireline, calibrated for stretch and temperature effects. These are standard drilling techniques for which standard QA/QC approaches are available.

11.5.2 Hydraulic testing

Some existing borehole sealing methodologies already incorporate downhole hydraulic conductivity testing on seals and on cement bonds behind casings. Downhole hydraulic testing undertaken by the oil and gas industry to verify the performance of borehole seals and casing bonds is described in subsection 4.3.8 of [1]. This hydraulic testing is undertaken in cased sections of borehole and generally involves monitoring the recovery of fluid pressure after imposition of either a positive or negative fluid pressure to the section to be tested. The section of borehole to be tested is isolated from the rest of the borehole through the use of an inflatable or mechanical packer.

Hydraulic testing during the sealing of boreholes at the site of a potential GDF could, in principle, be undertaken to determine the hydraulic conductivities of borehole seals, borehole support elements or casing cementation. Some of this hydraulic testing could be undertaken in cased sections of borehole. Other hydraulic testing could be taken in open sections of borehole, either in sections that had always been ‘open’ or in localised sections where casing had been removed to allow for borehole seals to be installed in direct contact with the surrounding rock. (See subsection 3.6.2 for a discussion on the removal of borehole casing.) The application of hydraulic testing of borehole seals, which are to be formed from bentonite, would be limited by:

- the necessity to physically confine the bentonite seal at the earliest opportunity to prevent it from expanding with consequent reduction in swelling pressure and increase in hydraulic conductivity;
- the importance of not damaging, or potentially damaging, the seal through inserting cabling or tubing through it. Any hydraulic testing can only be undertaken at the upper surface of the seal.

Given the above, opportunities for hydraulic testing of borehole seals would be limited. They should be considered on a case-by-case basis, dependent on the seal design and nature of the surrounding rock. There is more scope for hydraulic testing of support elements or casing cementation jobs, as there is no time constraint on hydraulic testing these components after emplacement. From a QA/QC perspective, approaches and controls for measurement of hydraulic pressure (or ‘porewater’ pressure) during borehole sealing would be as for the earlier characterisation phase.
11.6 **Summary**

This section has described the approach to QA/QC for borehole sealing. The key points are listed below.

1. The QA/QC framework described in this section is conventional, and has previously been applied on many similar projects involving borehole construction and sealing.

2. Planning for borehole sealing should start at the borehole design phase. Detailed records of the completed borehole should be kept, including records of casing schemes and any equipment/long-term monitoring systems installed in the borehole.

3. Many of the activities described in this section are well-developed and routinely applied within the context of modern QA/QC systems.

4. RWM will build confidence in any less well-developed approaches for sealing boreholes, for example placing bentonite using dump bailers, through further RDD.

5. Consequently, RWM does not foresee the need to monitor the borehole sealing system after emplacement (for example, through monitoring development of mechanical displacements or swelling pressures). RDD will provide confidence that the borehole sealing system can be installed in line with the design requirements and will provide an adequate understanding of the evolution of the seal properties and the longevity of the seal.

6. Measurements required to enable the borehole to be successfully sealed are of two types:
   a. measurements needed to design the borehole sealing system (the ‘boundary conditions’ for the seal) such as the borehole diameter, its variability and the groundwater composition, and;
   b. measurements to demonstrate that the borehole sealing system has been placed in accordance with the design, for example the depth of emplacement of materials in the borehole and the volumes of seal and support materials placed. We expect that opportunities for hydraulic testing of the borehole seal at emplacement would be limited; there is more scope for hydraulic testing of support elements or any casing cementation jobs.

Finally, RWM will continue to engage with other WMOs to share experience of borehole sealing and to seek opportunities for collaborative RDD. Further RDD into borehole sealing will also be undertaken as part of the RWM research programme. The approaches and methods presented here will therefore continue to develop, particularly in areas relating to the emplacement of bentonite in deep site investigation boreholes.
12  Recommendations for borehole sealing systems

12.1  Introduction

As discussed in subsection 3.3, the components of a borehole sealing system are ‘seals’ and ‘supports’. In addition to these two components, short deformable metallic plugs (termed ‘bridge plugs’) could potentially be used as part of some borehole sealing systems, either for support purposes or to limit geochemical interaction between seals and supports. Such bridge plugs would be formed from ductile metals expected to exhibit low corrosion behaviour when exposed to groundwater, as only such materials would ensure the integrity of the bridge plug over timescales of relevance to the Environmental Safety Case (ESC) for a GDF.

In the remainder of this section, we present the key features of recommended generic borehole sealing systems in HSR, LSSR and evaporite host rocks, and in any overlying cover rocks. In each case, we assume that the design of the borehole sealing system is in accordance with the principles described in subsection 3.5, that the required standard of borehole sealing is as described in Section 4 and that the borehole has been prepared for sealing as described in subsection 3.6.

An approach to optimising the arrangement of seals and supports in boreholes was presented in subsection 4.6. This, or a similar approach, should be used to support the design of any specific borehole sealing system. At the generic stage of RDD, the issue does not need to be considered further.

The standard of borehole sealing required by the ESC for a GDF will be a function of the geological environment, the disposal concept and the location of the site investigation borehole relative to the GDF. In addition, the borehole sealing system will be required to protect groundwater resources from other ‘threats’, such as naturally occurring saline water bodies and surface-derived anthropogenic contamination. A draft decision support tree was presented in section 9.6 of [2] to gain insight into the required properties of sealing materials in various possible circumstances. This decision tree has now been updated and sub-divided to reflect RWM terminology for the different geological environments. The updated decision trees are presented in the following sections.

12.2  HSR host rock

12.2.1  Decision support tree

Advection is the dominant transport mechanism in an HSR host rock; the potential effect of the borehole on groundwater flow from the GDF will depend on its location relative to the GDF. The decision support tree (Figure 12-1) identifies two broad classes of HSR: a rock in which groundwater flow occurs mainly in a few higher transmissivity fracture zones (‘discretely fractured’) and a rock in which groundwater flow is distributed across many fractures (‘densely fractured’).

In the case of a discretely fractured HSR, the borehole sealing approach is to isolate the higher transmissivity fracture zones from the borehole by sealing the lower permeability rock above and below the position at which the fracture zone intersects the borehole (see Figure 4-3). Support elements placed across higher transmissivity fracture zones should have low permeability at emplacement. A low permeability is not required in the longer term (see subsection 5.3). The support elements should also be able to withstand mechanical erosion (a significant groundwater flux in the fractures cannot be excluded) and provide long-term mechanical support to the overlying and underlying seals.

The required permeability of borehole seals placed in the HSR will be influenced by the requirements of the environmental safety case, and are discussed further below. The seal
material does not have to have a high resistance to mechanical erosion because little or no advective flow is anticipated in the rock away from the higher transmissivity fracture zones.

Figure 12-1  Decision support tree for borehole sealing in HSR (as host rock)

In the case where the HSR is characterized by a dense fracture network, isolation of individual fractures from the borehole will not be feasible. The seal will need to be placed directly across the individual fractures where they intersect the borehole. Notwithstanding this, mechanical erosion is unlikely to be an issue as the effective permeability of the HSR will need to be low for it to be suitable as a potential GDF host rock.

Section 10 demonstrated that there would be no requirement to seal a borehole in HSR against gas migration. Gas migration is a potential issue only in the case of an HSR host rock overlain by lower permeability cover rocks in a configuration that could cause gas accumulation in the vicinity of the borehole.

12.2.2 Principal features of borehole sealing system

The principal features of the recommended generic borehole sealing system for a HSR host rock are listed below. A key feature of the borehole (see subsection 2.6 for illustrative borehole designs and assumptions) is that it is expected to be in-gauge throughout its length except for where it passes through natural fracture zones. See subsection 2.7 for further details. The assumption below is that borehole in HSR will be un-cased.
Isolating higher transmissivity fracture zones from the borehole

Some or all of the higher transmissivity fracture zones that intersect the borehole in HSR should be isolated from the borehole to prevent or limit cross-flow through the borehole. The decision on which major fracture zones would require isolation should be informed by the output from site-specific groundwater flow and transport modelling studies and performance assessment calculations.

The sealing system around a higher transmissivity fracture zone should comprise:

- Bentonite seals installed in low permeability HSR above and below the higher transmissivity fracture zone. The minimum length of seal should be several tens of metres (consistent with the lengths of borehole seals used in other industries: see subsection 4.6.1 of [1] and discussion in subsection 3.3), unless constrained by the presence of an adjacent higher transmissivity fracture zone. The properties of bentonite that make it a suitable material for borehole seals were discussed in Sections 3, 5 and 8.

- A support element designed for higher transmissivity features, which should be placed at the elevation of the fracture zone\(^{28}\). Reference [9] identifies cementitious materials as being suitable for this purpose; the low permeability at emplacement will ensure adjacent bentonite seals can be installed without damage because of inflows or outflows to the borehole through adjacent higher transmissivity features\(^{30}\).

Metallic bridge plugs would be used if required. The circumstances under which bridge plugs would be required were discussed in subsection 5.3.3.

Three forms of bentonite could potentially be used for borehole seals in HSR: high density blocks, pellets and slurries. The required permeability of borehole seals in HSR has been estimated from modelling studies (subsection 4.4) and informed by reviews of work undertaken by other WMOs (subsection 4.3). The expected hydraulic conductivities of different forms of bentonite is shown by the relationships between density\(^{31}\) and hydraulic conductivity presented in Figure 5-2 and Figure 7-7, and the more detailed discussions in subsection 5.2.3. A comparison of these hydraulic conductivities with the requirements for borehole seals leads to the conclusion that all three forms of bentonite could achieve the required hydraulic conductivity in some circumstances. However, the bentonite swelling pressure will be substantially reduced in saline solutions, and in these situations a seal formed from bentonite slurry may not achieve the required hydraulic conductivity.

Consequently, bentonite blocks and pellets are recommended for forming borehole seals in HSR. The uniform diameter over long sections of borehole in HSR is particularly favourable for the use of bentonite blocks, which would also achieve the lowest seal hydraulic conductivities. Seals formed from bentonite slurry should only be considered if the groundwater composition is

\(^{28}\) Reference [9] sub-divides support elements into two classes; those suitable for emplacement in higher permeability sections of borehole and those suitable for emplacement in lower permeability sections of borehole. The former class is further sub-divided into supports for use in higher permeability rock units and supports across discrete higher transmissivity features such as fracture zones.

\(^{30}\) Note that the SKB reference design for ‘silica concrete seals’ (see subsection 2.5.5 of [1] for further details) is proposed for this purpose in the SKB borehole sealing concept.

\(^{31}\) The maximum dry density of a pumpable bentonite slurry formed from mixing fine-grained bentonite powder with water is estimated to be about 730 kg/m\(^3\). The bulk dry densities of the uniform-sized MX-80 bentonite pellets used in the laboratory programme [5, 6] were between 880 kg/m\(^3\) and 970 kg/m\(^3\). Values up to up to 1.45 kg/m\(^3\) are reported for a backfill formed from graded bentonite particles; a density of 1.3 kg/m\(^3\) can be reached using spherical balls of bentonite of a single size. The as-placed densities of pellets and slurries will be very similar to the bulk densities because both forms of bentonite can fully fill irregular-shaped volumes. The dry densities of the bentonite blocks used in the laboratory programme were approximately 1,900 kg/m\(^3\). The as-placed density would be lower if the block were used to fill an irregular-shaped volume.
favourable for their use and if there are site- and borehole-specific reasons why placing blocks or pellets is not practicable.

Emplacement using a dump bailer is considered the best approach for placing both the bentonite (as blocks or pellets) and any cementitious materials for use as support elements against higher transmissivity fracture zones. The advantages of this approach were discussed in subsection 6.3.3. Ideally, the dump bailer should be designed so that the chamber can be isolated from the fluid in the wellbore. In this way, the bentonite can be lowered into the borehole without coming into contact with any water. If this is not possible, the chamber should be designed such that the water composition in the chamber can be controlled as the dump bailer is lowered; a combination of dilute water (such as \(<0.1\text{M NaCl}\) and coated pellets or blocks should ensure that the bentonite does not swell before it is released from the dump bailer.

The method of deploying the dump bailer (on coiled tubing or core drilling equipment) is a borehole- and site-specific decision. Either coiled tubing or core drilling equipment are considered suitable at the generic stage.

**Remaining sections of HSR**

The remaining sections of borehole in HSR should be filled with a support element suitable for use in lower permeability sections of borehole. A range of materials suitable for support elements in low permeability sections of borehole was identified in subsection 5.3.1:

- cementitious materials;
- granular materials; and
- barite-based materials.

The advantages and disadvantages of using these materials were discussed in detail in [9]. The two stage screening and selection process described in subsection 5.3.2 should be used to select the most appropriate material.

Pumpable materials should be placed by pumping using coiled tubing or conventional pumping using drill pipe [4]. Granular materials should be placed by dump bailer, to prevent or minimize size separation caused by differing settlement speeds.

As previously, the use of metallic bridge plugs should be considered to limit chemical interaction between seal and support element or to confine the bentonite seal and prevent swelling before the overlying support element develops its confining properties.

The preferred approach to limit the consequence of chemical interaction between seal and support element should be to install a greater length of seal than is required, and to accept that the seal material in close proximity to the support may be degraded by interaction with the support element. If this is not possible, for example because adjacent higher transmissivity features intersecting the borehole prevent the use of a longer seal, then a bridge plug should be used instead.

### 12.3 LSSR host rock

#### 12.3.1 Decision support tree

The permeability of LSSR is very low. Consequently, diffusion is the dominant transport mechanism, even over distances of hundreds of metres. The properties of an LSSR host rock are likely to be such that the presence of a certain thickness of intact host rock between the GDF and the borehole will be sufficient to ensure that the borehole, even if left unsealed, will not have any significant post-closure impact on the groundwater pathway. In Figure 12-2, we describe such a borehole as being outside the ‘respect distance’. Because of the homogeneity of an LSSR host rock, the site characterisation strategy is likely to avoid drilling boreholes within the ‘respect distance’ of the GDF; that is, close to or within the GDF volume.
Figure 12-2  Decision support tree for borehole sealing in LSSR (as host rock)

Section 10 demonstrated that there would be no requirement to seal a borehole in an LSSR host rock against gas migration.

12.3.2  Sealing sections of LSSR

The principal features of the recommended generic borehole sealing system for an LSSR host rock are listed below. A key feature of the borehole (see subsection 2.6 for illustrative borehole designs and assumptions) is that it is expected to be over-gauge and of variable diameter throughout much of its length in the LSSR host rock (see subsection 2.7 for further details). The assumption below is that casing will have either been entirely removed or locally milled out to allow emplacement of borehole seals in direct contact with the rock.

The generic description of LSSR in the gDSSC is that ‘any movement of..... dissolved chemical species is dominated by diffusion through the rock matrix because any fractures that develop in these rocks will self-seal’. Therefore, unless the borehole is within the respect distance of the GDF, the very low permeability of the rock surrounding the borehole will limit the migration of dissolved radionuclides from the GDF to the borehole. As a consequence, a low permeability borehole seal will not be required by the ESC. Notwithstanding this, it is desirable to seal the borehole to limit the movement of any groundwater that might enter it. In the unlikely case that a borehole within the respect distance needed to be sealed, a low permeability seal providing a high hydraulic resistance is likely to be required.

If higher permeability interbeds or other features intersect the borehole, they should be sealed to prevent or limit cross-flow through the borehole. The decision on which interbeds or features would require sealing should be informed by the output from site-specific groundwater flow and transport modelling studies and performance assessment calculations.

The sealing system around a higher permeability interbed or other feature should comprise:

- bentonite seals above and below the higher permeability interbed or other feature. The minimum length of seal should be several tens of metres (see subsection 3.3);
a support element designed for higher transmissivity features should be placed at the
elevation of the interbed or feature. A cementitious-based material is considered suitable for
this purpose.

Based on reviews of work undertaken by other WMOs and the arguments presented above,
bentonite to seal a borehole located outside the respect distance in LSSR host rock could be in
the form of high density blocks, pellets or slurry. The irregular nature of the spaces to be filled
means that blocks may be less suitable for sealing than pellets and, potentially, slurries.

Emplacement using a dump bailer is considered the best approach for emplacing both bentonite
pellets and short sections of support materials across highly permeable zones. As with the HSR
case, the dump bailer should ideally be designed to isolate the contents from the wellbore fluid.
Failing this, the water composition in the chamber should be controlled to maximise slurry
density and ensure physical stability of the pellets, which should be coated to ensure that they
do not swell before release from the dump bailer. Bentonite slurry for borehole seals could be
placed by conventional pumping using drill pipe, pumping using coiled tubing or by using dump
bailers. The choice of technique will be influenced by factors such as borehole stability and the
length of bentonite seal to be emplaced.

The method of deploying the dump bailer (on coiled tubing or core drilling equipment) is a
borehole- and site-specific decision. Either coiled tubing or core drilling equipment are
considered suitable at the generic stage.

12.3.3 Remaining sections of LSSR

The remaining sections of borehole in LSSR host rock should be filled with a support element
suitable for use in lower permeability sections. If the borehole casing has been removed,
support elements will be placed in direct contact with the rock. If not, support elements will be
placed inside the casing. Casing removal and cementation was discussed in subsection 3.6.2.

The range of suitable materials, the screening/selection process and the methods of placing
support elements are all as described for HSR in subsection 12.2. Likewise, the potential use of
bridge plugs is as previously described for HSR in subsection 12.2.

12.4 Evaporite host rock (halite)

The permeability of halite is extremely low, and the rock provides a dry environment.
Consequently, groundwater transport in halite is absent or negligible except in any higher
permeability interbeds such as anhydrite. In an evaporite host rock, the ease of placing the seal
material means that there is no requirement for support elements; the full length of the borehole
in the halite host rock would be filled with seal material.

There are, potentially, two components of borehole seals in halite:

- the first component (if required) provides low permeability in the short term, before creep of
  the halite around the borehole has created a seal against the material within the borehole.
  The recommended material for this component of the seal is an appropriate cementitious
  formulation such as salt cement or Sorel cement. The choice of cement formulation would
  depend on the mineralogy of the evaporite in contact with the borehole;

- the second component is always required, and provides a seal in the longer-term, after
  creep of halite against the material within borehole is complete. Because of this creep, this
  second component of the borehole seal can be formed from either a naturally occurring
  evaporite mineral (such as crushed halite) or an appropriate cementitious formulation.

The decision support tree in Figure 12-3 shows the two scenarios described in subsection 9.2.1;
a borehole that fully penetrates the halite layer and a borehole that partially penetrates the halite
layer.
In the case of a fully penetrating borehole through the halite host rock, groundwater flow through the borehole will be driven by head differences across the halite layer, and will result in dissolution of the halite surrounding the borehole. The timescale on which this dissolution will occur depends on whether the borehole is cased or uncased; in either case it will occur on a timescale of relevance to the ESC. To prevent continuing groundwater flow and halite dissolution, the borehole should be sealed using components that provide low permeability in both the short term and longer term.

For the purposes of sealing a fully penetrating borehole in bedded halite formations, we recommend that an appropriate cementitious formulation, such as salt cement or Sorel cement, be used at the upper and lower boundaries of the halite formation to protect against halite dissolution and/or long-term groundwater flow through the borehole. The choice of cement formulation would depend on the mineralogy of the evaporite in contact with the borehole. The central element of the borehole seal could be formed from crushed salt or other evaporite minerals (depending on the mineralogy of the evaporite in contact with the borehole) or by a suitable cement formulation. Because the composition of seals would depend on the site evaporite mineralogy, RDD to design such seals should be left until the site-specific stage of the GDF siting programme.

In the case of a partially penetrating borehole through the halite host rock, there is no potential for groundwater flow through the borehole unless it intersects permeable interbeds within the halite. Hence, it is not essential to place a cementitious seal at the upper surface of the halite to provide low permeability in the short term. However, a seal component that provides low permeability in the longer term will always be required. If a cementitious seal is not to be used to
provide low permeability in the short term, it will be necessary through scenario analysis to demonstrate that there would be no adverse outcomes from its omission. In practice, it is likely to be more straightforward to include a seal component that provides short term permeability rather than to attempt to justify its omission.

12.5 **Cover rocks**

12.5.1 **Introduction**

The requirement for placing borehole seals (as opposed to support elements) in sections of cover rock will depend on the nature of the cover rocks, in particular the presence of:

- laterally extensive low permeability horizons, which act to improve geosphere containment by further isolating the deep groundwater system around the GDF from the shallower groundwater system, and;
- the presence of groundwater resources (i.e. aquifer units) within the cover rocks, which would need protecting against inflow from underlying saline groundwater bodies or from overlying anthropogenic contamination.

The locations and numbers of any borehole seals required to ensure geosphere containment and groundwater resource protection should be informed by the output from site-specific groundwater flow and transport modelling studies and performance assessment calculations. The seals would be placed in direct contact with the rock within low permeability horizons to prevent or limit cross-flow along the borehole axis. This would require the borehole casing to have either been entirely removed or locally milled out. The locations and numbers of any borehole seals required to protect groundwater resources should be chosen following agreement with the environmental regulator.

It is anticipated that most of the length of the borehole within cover rocks would be filled with support elements. If the borehole casing has been removed, support elements will be placed in direct contact with the rock. If not, support elements will be placed inside the casing. Casing removal and cementation was discussed in subsection 3.6.2.

12.5.2 **Seals**

Borehole seals in cover rocks should be formed from bentonite and placed in sections of lower permeability rock. The minimum length of seal should be several tens of metres, unless constrained by the thickness of the low permeability horizon or by the presence of higher permeability or transmissivity horizons that intersect the borehole.

Given the likely variability in diameter of a section of uncased borehole to be sealed, and the possibility that the seal is to be installed in a section of locally milled out casing, suitable forms of bentonite would be pellets or slurry. The emplacement of such seals would be as for LSSR host rocks (subsection 12.3.2).

As discussed in Section 10, the one scenario where a decommissioned site investigation borehole can become an important part of the gas pathway is where the borehole intersects LSSR in a region where accumulation of GDF-derived gas is possible³². In this scenario, it was recommended that the borehole seal should be designed to prevent or minimise gas migration. It will be necessary that the bentonite seal re-saturates before the gas phase has migrated to the location of the borehole; this may influence the choice of the form of bentonite (pellet or slurry) selected for the seal.

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³² A particular example of this scenario might have an anticline structure, with the LSSR overlying more permeable rocks. Gas could accumulate beneath the LSSR, and then potentially migrate up a nearby borehole.
12.5.3 Support elements

Sections of borehole to be closed using support elements should be categorized as:

► locations where higher transmissivity features, such as fracture zones, intersect the borehole;

► intervals where lower permeability rock intersect the borehole;

► intervals where higher permeability rock units intersect the borehole.

Support elements for use in both the 'higher transmissivity features' and 'higher permeability rock units' environments will be chosen to be resistant to erosion by flowing groundwater; see subsection 5.3.1. Support elements for use in the 'higher transmissivity features' environment will additionally require short-term low permeability to ensure that adjacent seals can be installed correctly.

The boundary in rock properties between lower and higher permeability rock will need to be defined using site-specific and borehole-specific criteria. At the generic stage, it is sufficient to recognise that rock types that exhibit higher permeability include many sandstones and limestones; rock types that exhibit lower permeability include mudstones, meta-mudstones and meta-sandstones. See Figure 3 from RWM's Geosphere Status Report [18].

A cementitious-based material is considered suitable as a support element for emplacement against higher transmissivity features. A dump bailer is considered the best approach for placing the cementitious material. Support elements for lower permeability section of borehole are as described for HSR in subsection 12.2.

Cementitious materials and coarser-grained granular materials such as crushed rock are considered suitable as support elements for higher permeability sections of borehole. At the present, generic, stage, barite-based materials (excluding barite-bearing cementitious materials), bentonite-quartz mixtures and graded silica are all considered to be unsuitable. The reason is that these materials are both fine grained and unconsolidated (uncemented), such that erosion could be a problem. Further RDD would be needed to determine if graded silica could be suitable as a support material if the maximum particle size could be increased such that it was larger than the fracture or pore apertures.

The selection process described in subsection 5.3.2 should be used to select the most appropriate material.

Pumpable materials should be placed using coiled tubing, which offers a higher degree of control than conventional pumping. Granular materials should be placed by dump bailer, to prevent or minimize size separation caused by differing settlement speeds.

The factors to be considered when deciding whether or not to use bridge plugs are as presented in subsection 5.3.3.
13 Conclusions and recommendations

This report presents a summary of the work undertaken during a three year project (Sealing of deep site investigation boreholes: Phase 2) to develop generic approaches to seal deep boreholes drilled as part of site investigations at a potential Geological Disposal Facility (GDF) site. It concludes by making recommendations for generic borehole sealing systems in the geological environments relevant to RWM’s siting process for a GDF.

In the project, we define the ‘borehole sealing system’ as the overall system for sealing a site investigation borehole. In most instances, the borehole sealing system comprises a combination of ‘seals’ and ‘supports’, which completely fill the borehole. In some cases, short deformable metallic bridge plugs could potentially be used at the interface between seals and supports for a variety of purposes. Such bridge plugs would be formed from ductile metals expected to exhibit low corrosion behaviour when exposed to groundwater, as only such materials would ensure the integrity of the bridge plug over timescales of relevance to the Environmental Safety Case (ESC) for a GDF. Definitions of these components are given in subsection 3.3. The illustrative designs of the boreholes that will require sealing are given in subsection 2.6. A key feature is that they will be up to 2,000m deep.

This section of the report presents the main conclusions from the project (subsection 13.1) and makes recommendations for further generic RDD to enable RWM to demonstrate that approaches are available for sealing deep site investigation boreholes against groundwater flow and gas migration in a range of geological settings potentially relevant for a UK GDF (subsection 13.2).

13.1 Conclusions

The main conclusions of the project are summarised below.

13.1.1 Requirements for borehole sealing systems

The project has identified the following requirements for borehole sealing systems.

1. The required permeability of the borehole seal should be informed by the environmental safety case rather than by a requirement to return the rock to its pre-drilled condition. The project has concluded that:
   a. from a GDF performance assessment perspective, borehole seals in HSR host rock need not have a permeability as low as that of the HSR itself. For example, the 2012 SKB Closure Report proposed the following design premise with respect to long-term safety for sealing of investigation holes at Forsmark: ‘The resulting hydraulic conductivity over the length of the borehole shall be lower than 10^{-6} ms^{-1}’;
   b. in the case of LSSR or evaporite host rocks, site-specific modelling of sites outside the UK undertaken by overseas Waste Management Organisations confirms that sealed boreholes can have hydraulic conductivities of up to 10^{-5} or 10^{-6} ms^{-1} without significantly affecting radionuclide flux out of the geosphere.

2. In addition to the requirements from the GDF performance assessment, the borehole sealing system is required to protect groundwater resources from adjacent saline groundwater bodies and/or from overlying anthropogenic contamination.

3. The design of investigation boreholes at the site of a potential GDF, and of any long-term monitoring installations placed in them, should take account of the need for subsequent borehole sealing.
4. A tiered set of requirements for borehole sealing systems in generic geological environments has been developed. Higher level requirements must be fulfilled before lower level requirements are considered.

In practice, this implies a preference for:

a. concepts requiring only a limited number of steps for implementation;
b. demonstrated/proven emplacement techniques;
c. concepts in which the lengths of component sections (i.e. seal or support element) are long enough to ensure emplacement at the specified depths.

5. The modelling approach developed in the Phase 2 borehole sealing project should be used to explore optimisation of the arrangement of seals and support elements in a range of geological environments potentially relevant to RWM.

6. Gas migration through a sealed site investigation borehole is a potential concern only where the borehole intersects lower permeability cover rocks in a region where accumulation of GDF-derived gas is possible. In this case, the requirement is that the bentonite seal must fully re-saturate before the gas phase has migrated to the location of the borehole. This will influence the choice of the form of bentonite (high density block, pellet or slurry) selected for the seal.
13.1.2 Materials

The project has identified the following materials as being suitable for use in generic borehole sealing systems.

7. Borehole seals in HSR and LSSR should be formed from bentonite.
   a. High density bentonite blocks, pellets and slurries should all be considered as materials for forming borehole seals in HSR and LSSR. The optimum form of bentonite chosen to seal the borehole will depend on the geometry of the space to be sealed, the ease of emplacement and the required hydraulic conductivity of the borehole seal.
   b. The hydraulic conductivity and swelling pressure of a bentonite seal will be controlled by the placed dry density of the bentonite, the proportion of swelling clay mineral in the bentonite and the composition of the groundwater in contact with the bentonite. These relationships can be used to determine which emplacement techniques and forms of bentonite (blocks, pellets, slurries) can achieve the required hydraulic conductivity for a borehole seal in a given groundwater composition.
   c. That said, this report makes it clear that the standard of borehole sealing that can be achieved using bentonite pellets or blocks is likely to be significantly higher than required by the ESC. The laboratory experiments undertaken as part of this project show calculated hydraulic conductivities of less than $10^{-8}$ m s$^{-1}$ with seals formed from bentonite pellets, and of less than $10^{-11}$ m s$^{-1}$ with seals formed from bentonite blocks. These hydraulic conductivity values are very much lower than the acceptable hydraulic conductivities quoted in paragraph 1 for sealed boreholes in a range of geological environments. This indicates that borehole seals formed from bentonite are expected to yield hydraulic conductivities that are suitable for the purposes of borehole sealing.
   
   Note that the bentonite pellets used in the tests reported here have not been optimised to maximise their placed density. The use of pellets with different shapes and sizes, including the use of pellets with a range of sizes, could result in different, and potentially greater, placed densities to those reported here. It is possible that significantly lower hydraulic conductivities could be achieved through optimising placed density.
   d. Bentonite is susceptible to mechanical erosion by flowing groundwater. Therefore, it should not be used in higher permeability sections of borehole. Bentonite is also susceptible to chemical erosion in dilute groundwater. Such dilute groundwaters are unlikely to occur at GDF depth in potentially relevant geological environments under current UK climatic conditions. They might occur at GDF depth in some areas of the UK during future periods of glaciation. We recognise that the EU-project BELBaR developed a better, and less cautious, representation of the processes that control bentonite erosion. Although this work was directed towards a better understanding of bentonite erosion in repository engineered barrier systems, the learning will also be relevant to understanding bentonite erosion in borehole seals. Note that there are no identifiable erosion vulnerabilities associated with any future increases in groundwater salinity.

8. Borehole seals in evaporite could be formed from natural evaporite minerals and/or from appropriate cementitious materials, such as salt-saturated cement or Sorel cement. Creep of halite around an uncased borehole will ensure long-term sealing against whatever materials are placed in the borehole. Before this occurs, natural materials such as crushed halite will not provide a low permeability seal; only cementitious materials can provide a low permeability seal during this period.
   a. The composition of borehole seals in evaporites (either formed from natural evaporite minerals or from an appropriate cementitious material) will depend on the site evaporite mineralogy; selection of materials for such seals should be left until the site-specific stage of the GDF siting programme.
b. An appropriate cement formulation, such as salt cement or Sorel cement, should be used at the upper and lower boundaries of the halite formation to protect a borehole seal formed from halite until it has consolidated and achieved low permeability.

9. Three groups of materials suitable for support elements in HSR and LSSR have been identified. Selection of a support element material for a particular borehole can only be undertaken once site-specific and project-specific information is available.

a. The following materials are considered suitable as supports in lower permeability sections of borehole: cementitious materials; granular materials (crushed rock, crushed rock-bentonite mixtures, bentonite-quartz mixtures and graded silica), and; barite-based materials.

b. The following materials are considered suitable as supports in higher permeability sections of borehole: cementitious materials and coarse granular materials. The reason for omitting fine grained and unconsolidated (un-cemented) materials is that erosion could be a problem. Graded silica could be suitable in high permeability sections of borehole if it can be formulated to behave as a Bingham Plastic, but further RDD would be needed to demonstrate the conditions, if any, when it could be used.

13.1.3 Emplacement

The project has identified the following emplacement techniques as being suitable for use in generic borehole sealing systems.

10. Seal materials should be placed in direct contact with the rock. In cased boreholes, the casing will need to be removed, for example by localised milling, before the seal is placed.

11. Dump bailing is a very promising technique, because of its simplicity and reliability, and we recommend it should be used to place bentonite as blocks or pellets and to place support elements for use at locations where higher transmissivity features, such as fracture zones or permeable interbeds in the host rock, intersect the borehole. The project has identified that suitable dump bailers can, in theory, be developed for this purpose.

12. Bentonite slurry for borehole seals could be placed by conventional pumping using drill pipe, pumping using coiled tubing or by using dump bailers. The choice of technique will be influenced by factors such as borehole stability and the length of bentonite seal to be emplaced.

13. Longer sections of support materials for use in higher or lower permeability sections of borehole can be placed using conventional emplacement techniques used in the oil and gas industry.

13.1.4 Recommendations for borehole sealing systems

14. Recommendations for borehole sealing systems have been made for the three illustrative GDF host rocks (HSR, LSSR and evaporite) considered in the generic DSSC (gDSSC) and for any overlying cover rocks.

13.2 Recommendations for further RDD

Two main areas for further generic RDD have been identified during the Phase 2 Sealing Deep Site Investigation Boreholes project. Firstly, as we recognised in subsection 5.2.3, the bentonite pellets used in the experiments reported here have not been optimised to maximise their ‘as-placed’ density. It is recommended that further work be undertaken to determine whether emplacement of spherical bentonite pellets or bentonite pellets with a range of particle sizes could be achieved in a deep borehole and result in an homogeneous seal with an increased ‘as-placed’ bentonite density’. For example, randomly packed uniform spheres could achieve a packing density of more than 0.6, which is consistent with previous assertions that the final dry density achieved by pellets in some applications is about 1,200 kg m$^{-3}$. 
Second, RDD would be needed to develop a dump bailer optimised for the emplacement of bentonite. In the short term, generic RDD would be needed to demonstrate that the bentonite can be successfully released from the bailer. This is likely to consist of large-scale laboratory tests in high headroom laboratories to simulate release of bentonite from the dump bailer and to determine the properties (such as density and hydraulic conductivity, and their heterogeneity) of the bentonite seal formed. Following on from this, it is likely that a suitable dump bailer would need to be designed and manufactured, and that field trials in boreholes would need to be undertaken to demonstrate that seals can be emplaced in accordance with the design requirements.

In addition, the radioactive waste management community continues to undertake RDD activities to build understanding of the performance of bentonite as a buffer/backfill material in the EBS of a deep geological repository. The potential application of this developing knowledge base to sealing site investigation boreholes should be kept under review.

In the longer term, after one or more communities have expressed interest in hosting a GDF, RWM will undertake further generic research into borehole sealing that will focus on geological environments relevant to these communities. Note that, even when the ISE has been completed, conceptual designs for borehole seals and supports will not have been fully optimised, and may provide a higher degree of sealing than is required from purely technical considerations. Once an intrusive surface-based site investigation is underway, RWM will use the outcome from research such as that undertaken in the Phase 2 borehole sealing project and in the ongoing Phase 3 borehole sealing project (which started July in 2017) as the basis of understanding from which to develop a programme of site-specific RDD on borehole sealing.
14 References


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[33] Marriott Drilling Group, Review of existing dump bailer technology and suggested modifications for borehole sealing, Marriott Drilling Group Report AFW 2017/1, 8 February 2017
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