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Development of Sealing Materials for Application as Engineered Barriers in a Deep Geologic Repository for Used Fuel Disposal: Filling the Gaps

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ABSTRACT

Concepts for the deep geologic disposal of used CANDU® fuel generally have most of the excavated emplacement-room volume filled with the waste-package and pre-manufactured sealing system components (e.g. highly compacted bentonite, bentonite-sand buffer, densely compacted backfill). In addition to these components, gaps are present between the various components and between the components and the rock perimeter that need filling. Materials to fill these gaps are generally referred to as gap fill (GF) or light backfill (LBF) and they play an important role in ensuring that the entire sealing system performs as intended.

GF and LBF materials are particularly important in ensuring that the used fuel container is protected from adverse effects such as excessive displacement of the surrounding sealing materials and microbially-influenced corrosion. Maximizing the density and minimizing the water activity (a_w) of the materials placed within these gaps are important in ensuring that adjacent materials maintain their 'as-placed' condition as closely as possible and that areas immediately adjacent to the containers do not become conducive to microbial activity.

In this paper, potential GF and LBF materials are investigated and their potential effects on the activity of the microbial population within the sealing system are described.

I. BACKGROUND

A number of generic deep geologic repository concepts have been developed and assessed for safely disposing of Canada's used CANDU® fuel inventory.[1,2] All of these concepts involve the emplacement of corrosion-resistant containers holding used fuel into an engineered facility located 500- to 1000-m below the surface in a crystalline (e.g., granitic) rock mass. Three generic waste-emplacement concepts considered for use in a deep geologic repository are presented in Figure 1. These concepts require the excavated emplacement-room volumes to be filled with used-fuel containers and pre-manufactured, sealing-system components (e.g., highly compacted bentonite (HCB), bentonite-sand mixture (buffer), densely compacted backfill (DBF)). Physical clearances are needed to allow their assembly and installation. Within an emplacement room are two or three

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regions where voids and gaps must be filled to ensure continuity of heat transfer and to facilitate sealing system performance over the longer term.

These regions includes the:

1. gap between the used-fuel container and the surrounding HCB or buffer;
2. gap between the buffer/HCB and the rock perimeter in a borehole emplacement geometry; and
3. void or gap between the precompacted blocks of HCB, buffer or DBF and the rock perimeter.

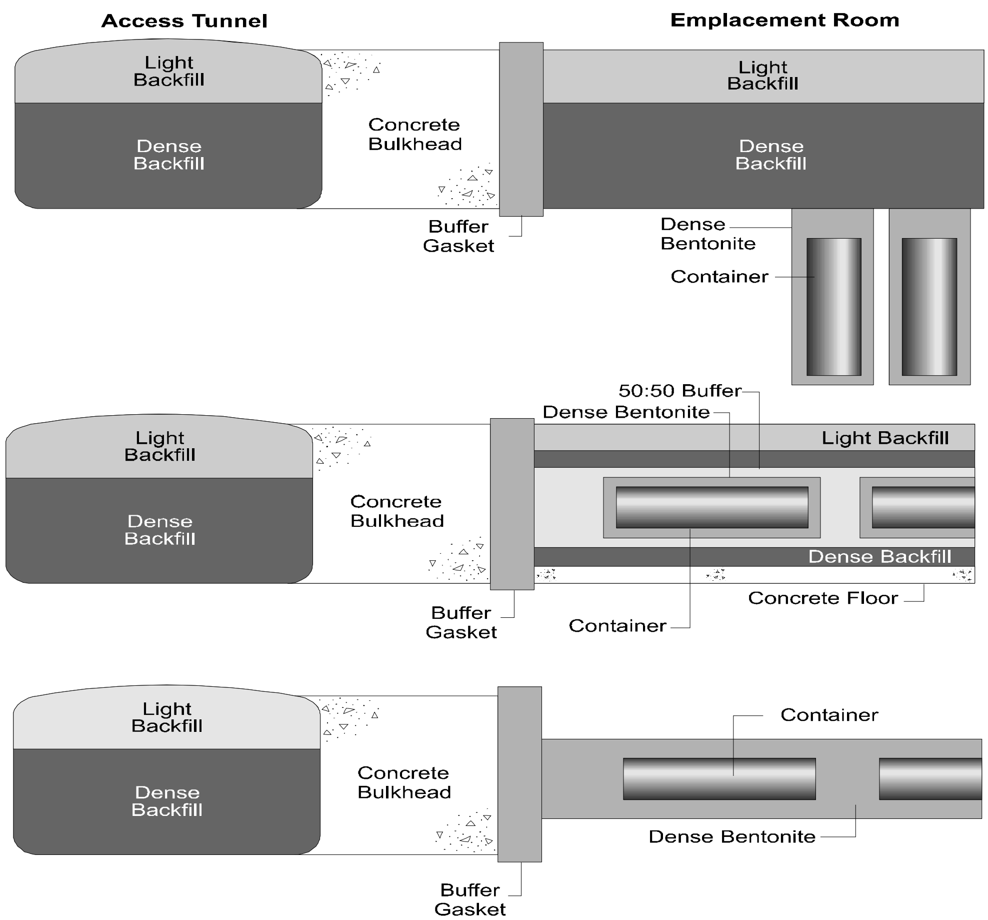


Figure 1: Generic In-Floor, In-Room and Horizontal Horizontal-Borehole Emplacement Concepts[2]

Narrow gaps require gap fill (GF) and larger voids require light backfill (LBF). Both serve the same basic functions as discussed below.

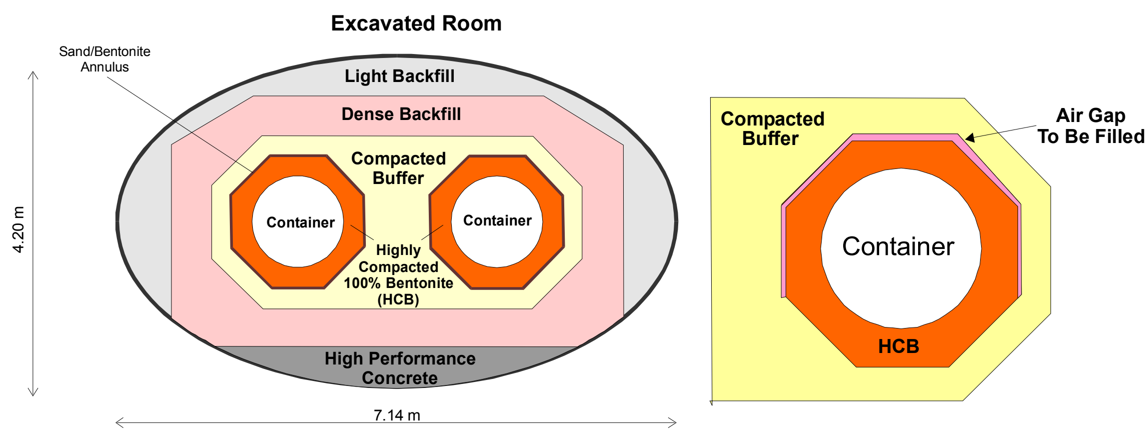
Heat is generated within a geologic repository from the radioactive decay of used fuel in the emplaced containers. A continuous, thermally conductive pathway between the containers and the surrounding rock mass is needed to limit the resultant temperature rise in the vicinity of the containers and potential thermal impacts on sealing system performance. The presence of air gaps between sealing-system components represents a significant thermal discontinuity and drives up temperatures.[3,4]

The portion of the rooms or tunnels that cannot be filled with dense, precompacted or compacted-in-place materials (HCB, buffer, DBF) needs to be filled with a material that will ensure that the used-fuel container is protected from displacement within the surrounding sealing materials, any generation of a flow path along the room perimeter and any reduction in the density of the other sealing materials as they swell to fill gaps.

In addition to the thermal, hydraulic and mechanical issues that require the use of GF and LBF materials in a repository, the container must be protected from microbially-influenced corrosion (MIC)[5]. Microbial activity is suppressed by high bentonite-clay densities[6] and filling voids and gaps minimizes the ability of the clay to expand, limiting changes to the porosity of the system.

Gap Fill Materials

A number of constraints affect the installation and the achievable density of GF. The primary constraint is the size of the gap into which GF must be installed. In an in-room emplacement geometry (Figure 2a), the gap thickness is not uniform between the container and the surrounding precompacted materials (Figure 2b). A vertical, in-floor-type installation provides a more uniform gap although the container may be off-centred within the borehole (Figure 3a). Placement in a horizontal borehole also results in a non-uniform gap (Figure 3b). The vertical emplacement geometry may have a second annular gap present between the borehole walls and the precompacted buffer material (Figure 3a).

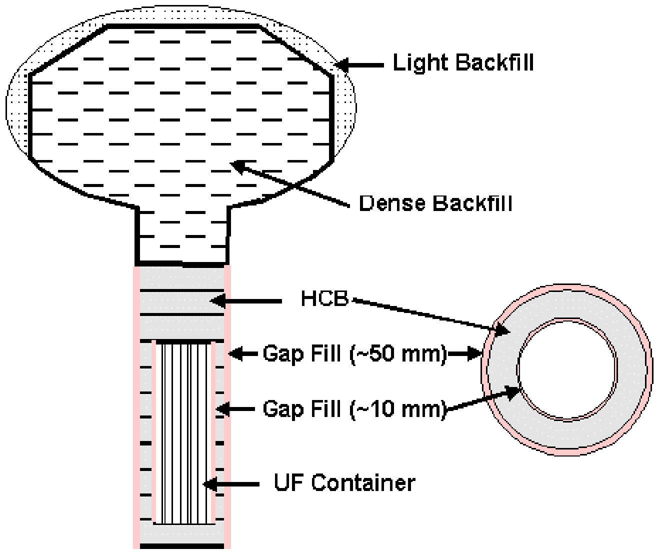


(a) Horizontally-Installed Container **(b) Detail Showing Air-Gap**

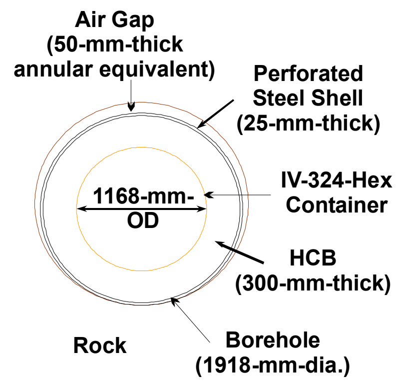
Figure 2: Gaps Present in the In-Room Emplacement Geometry[7]

Light Backfill Materials

The void dimensions for light backfill can be quite variable and large (e.g., 10s of centimetres) between the sealing materials and excavation perimeter (Figures 2a and 3a). As a result, the LBF is required to be readily installed at a consistent density in reasonably large quantities at rates compatible to other emplacement operations. Mechanical densification of LBF is unlikely due to the lack of sufficient space following, or in the course of its placement. Therefore, materials that can be installed at suitable densities without any special compactive effort must be identified.



(a) In-floor Borehole



(b) Horizontal Borehole[8]

Figure 3: Schematic Showing Gaps Present in Borehole-Emplacement Geometries

II. DEVELOPMENT OF GAP FILL AND LIGHT BACKFILL

Gap Fill

The GF, despite its small volume relative to the other sealing materials, can play a significant role in determining the performance of the system. For example, microbial activity at the surface of containers may lead to MIC, requiring the maintenance of high-density bentonite clay to create an environment hostile to microbial activity.[6] High-density bentonite clay can provide, firstly, very small pore-sizes and, secondly, a low value in water activity (a_w), both unfavourable for microbial activity.[6,10]

To ensure adverse conditions against microbial activity, the region immediately adjacent to the container requires a suggested a_w less than 0.96.[6] A low a_w environment can be achieved by using water-saturated, bentonite-based materials with high effective-montmorillonite dry densities (EMDD) greater than 1.35 Mg/m^3 (Figure 4).[10] EMDD is defined as follows:[11]

$$\text{EMDD} = \frac{M_m}{(V_m + V_v)} \tag{1}$$

where M_m = dry mass of montmorillonite clay; V_m = volume of the montmorillonite minerals; and V_v = volume of voids.

Water activity a_w is affected by the salinity of the pore fluid in 2 ways: (1) increasing salinity results in decreased swelling pressure of the montmorillonite (Figure 4);[13] and (2) increasing salinity of the pore fluid reduces the value of a_w (Figure 5).[12] When both the swelling pressure and solution concentration effects are combined and displayed as a function of the sealing system EMDD (Figure 6), then a means of dealing with microbial activity over the longer term (saturated environment) can be developed. Reliance on container heating to dry sealing materials as a control over microbial activity in the long term is not appropriate due to the supply of high-pressure groundwater from the surrounding rock mass and the expectation that the system will achieve saturation over the relatively short term (10s to 100s of years).

Studies of GF placement technologies and achievable densities were performed at AECL's Underground Research Laboratory (URL), using the principles leading to Figure 4.[13,14] The goal was to determine the EMDDs that could be achieved using simple and practical placement technologies and then compare these results to the a_w of equilibrated GF and HCB systems. A variety of filler materials were investigated including high-density precompacted pellets and blends of various sized materials. Gaps, 10- to 50-mm wide, were simulated by spaced parallel sheets of transparent plastic to represent the uniform spacing of an in-floor type of container emplacement (Figure 7). Into this gap, dry, particulate materials were simply poured into, or poured into and then vibrated or poured into and gently tamped. GF materials could be readily obtained and placed at EMDDs ranging from ~0.8 Mg/m^3 for 10-mm gaps to ~0.9 Mg/m^3.[14]

As the HCB swells and generates high-swelling pressures with water inflow, the adjacent gap-fill materials will compress and any other remaining gaps or voids in the nearby sealing system will fill. The amount of HCB expansion is directly related to the volumes and densities of the HCB and adjacent GF. In time, the HCB and GF portions will become water saturated and, at some later time, their densities should approach equilibrium. At equilibrium, bentonite-clay rich GF and HCB sealing materials surrounding the container are assumed to become homogeneous. The a_w of the system must be maintained at less than 0.96. If the volume of the gaps is too large or the materials beyond the GF and HCB too compressible (i.e., the in-room geometry), then the density of the materials placed within them becomes too low and the ability of the system to maintain an environment that is hostile to microbial activity may be compromised.

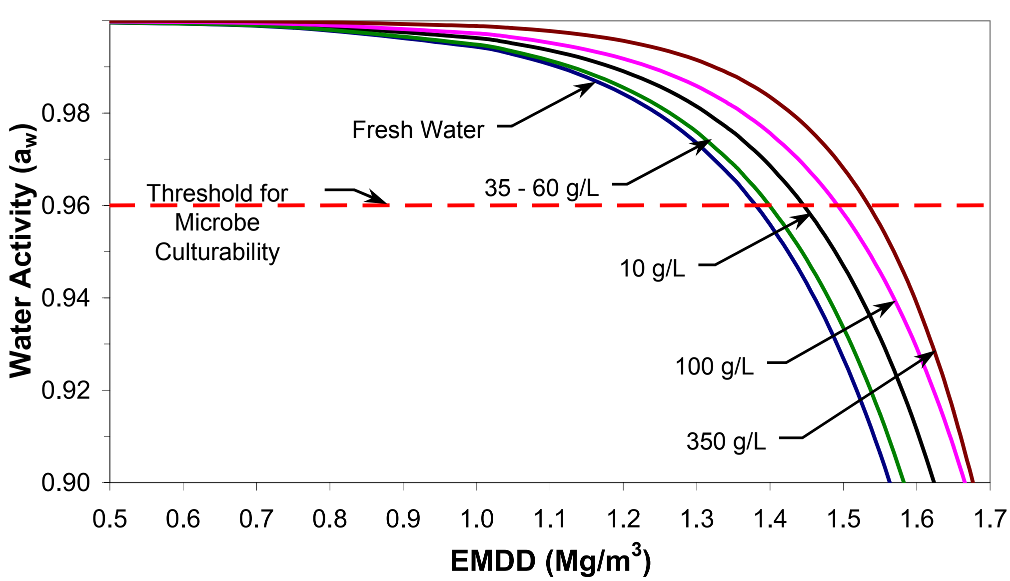


Figure 4: Relationship between Water Activity (a_w) and Swelling Pressure Influenced by EMDD and Pore-fluid Salinity for Bentonite[13,14]

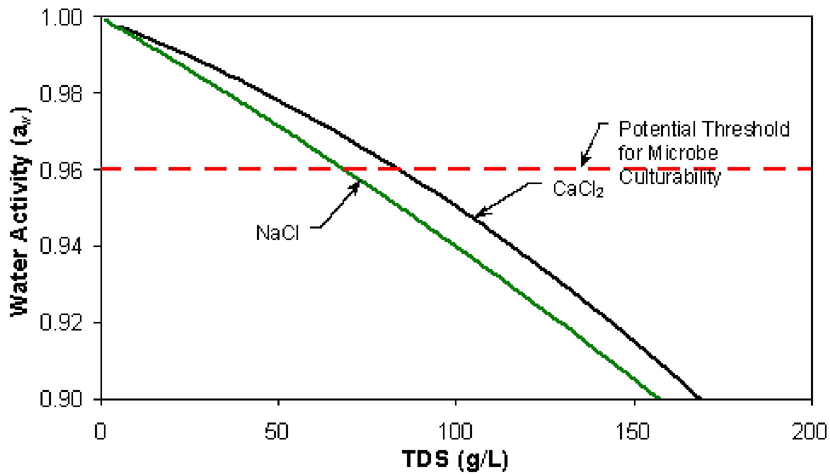


Figure 5: Relationship between Water Activity (a_w) and Pore-fluid Concentrations for NaCl and $CaCl_2$

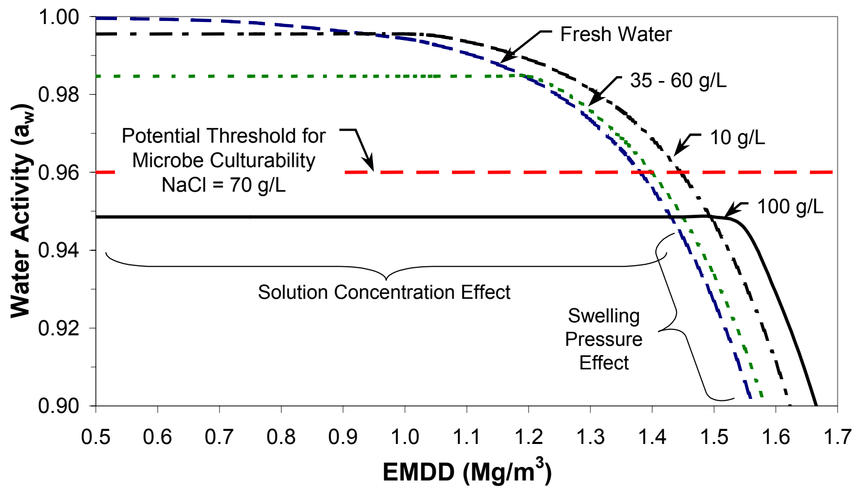


Figure 6: Possible Relationship between Water Activity (a_w) as Functions of Swelling Pressure and Pore-fluid Concentrations (see Figures 4 and 5)

The equilibrium EMDD varies with the 'as-placed' densities and dimensions of each component of the sealing system. For example in the in-floor or horizontal borehole emplacement geometries (Figures 3a and 3b), the borehole walls provide rigid confinement. Challenges exist in placing GF, especially in the horizontal geometry where the gap dimension is not uniform. For the in-floor borehole geometry (Figure 3a), equilibrium EMDD conditions can be readily calculated for various GF and HCB dimensions and densities. Examples of these types of estimates are provided in Figure 8.

The EMDD of GF, by itself, is insufficient to produce a hostile microbial environment. The maximum EMDD achieved in placement trials was ~0.9 Mg/m^3 which corresponds to an a_w of >0.995.[14] Achieving very high GF densities was not expected but maximizing the GF density will limit the density loss of the adjacent sealing materials. For example, the precompacted HCB immediately surrounding the emplaced containers is expected to have an EMDD of 1.4 Mg/m^3 or higher (i.e., dry density of at least 1.6 Mg/m^3).[2]

The combined or averaged sealing system EMDDs are calculated at the cross-section of the container in the in-floor borehole emplacement concept assuming the annular-gap dimensions shown in Figure 3a. Figure 8 shows the range of averaged sealing system EMDDs for a range of HCB and GF EMDDs, assuming that the combined materials will ultimately equilibrate or homogenize after system saturation and swelling. The HCB component dominates the value of the equilibrated EMDD, but the addition of GF plays a role in minimizing the loss in HCB density. For example, assuming a GF EMDD of 0.9 Mg/m^3 and that the HCB has a dry density of 1.8 Mg/m^3 (EMDD of 1.63 Mg/m^3) an equilibrated system will experience a density decrease of ~0.08 Mg/m^3 (~5%) to an EMDD of ~1.55 Mg/m^3. For a system having no GF component a density decrease to ~1.48 Mg/m^3 (9%) would occur.

Figure 7: Placement Trial in Simulated Annular Gap[14]

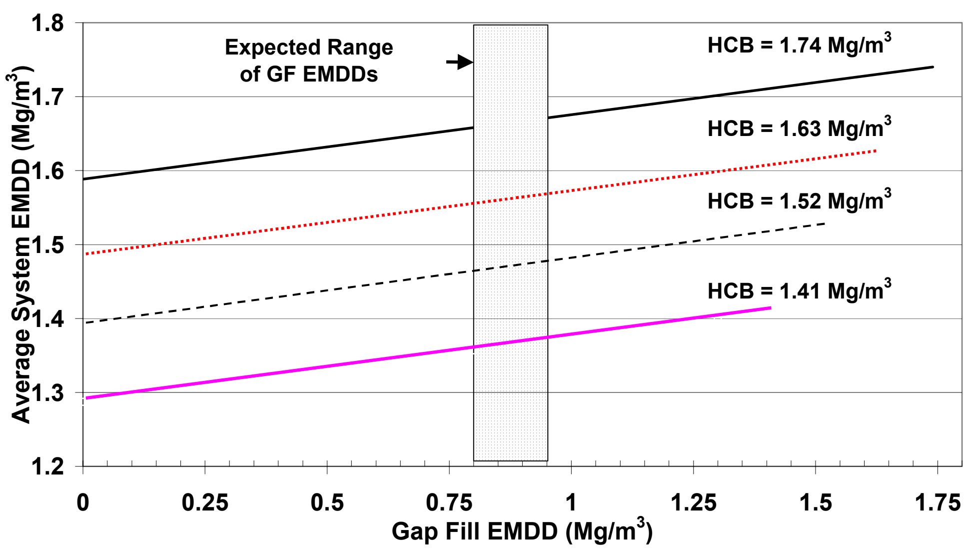


Figure 8: Relationship between Gap Fill EMDD and Resulting Average EMDD for the In-floor Borehole Emplacement Geometry

Average system EMDDs in the range of 1.35 to 1.57 Mg/m^3 (Figure 8) can be achieved within a rigidly constrained emplacement geometry using materials that are within the range of current production technology. Resultant water activities a_w should be less than 0.96 (Figure 6). Any increases in HCB and GF densities will, correspondingly, increase EMDDs and decrease a_w with the likelihood of enhancing a hostile environment against microbial activity at the contact of the bentonite with the container, thereby reducing the potential for MIC in this region.

Light Backfill

Like the GF, the LBF limits the amount of free swell (e.g., density reduction) of the buffer and HCB, which affects the potential for microbial activity (i.e., MIC). If the LBF is too compressible, then the density of the HCB may experience a density reduction to the point where the environment is no longer hostile to microbes.

The LBF must also maintain a positive contact with the materials adjacent to it (i.e., the DBF and the surrounding rock) to minimize mass transport along these contacts. The LBF must be sufficiently dense to limit hydraulic flow and be able to withstand the effects of high groundwater salinity on hydraulic conductivity. Highly saline groundwater anticipated to be present at depth in the Canadian Shield will increase the hydraulic conductivity of bentonite-based materials. In order to limit this effect the LBF needs to be consistently placed at as high a density as practicable.

An important function of the LBF, in addition to its sealing function, is to restrain the deformation and swelling of the other sealing materials. In the in-room emplacement method (Figures 1 and 2), the two ~23.5 Mg used-fuel containers will exert a lateral force, in addition to their weight, caused by the wedging action associated with their shape. Without the lateral restraint provided by the LBF on the sidewalls of the room, the heavy container may settle excessively. This restraint process also applies to the LBF along the roof of the excavation in that any plastic deformation of the sealing materials, including the lateral LBF, can lead to extrusion of the sealing materials into roof space if no LBF is placed in this region.

A variety of approaches have been attempted in dealing with filling the upper and side perimeter regions of an excavation. In the Tunnel Backfilling Experiment at the Äspö Hard Rock Laboratory in Sweden, the crown regions were filled with combinations of manually placed blocks of HCB and HCB pellets (see Figure 9).[15] For safety reasons, this approach is not likely to be practical in an operational repository, particularly if the in-room emplacement geometry is used. Alternative approaches include the placement of HCB pellets into the perimeter regions using mechanical or pneumatic technologies. A NAGRA emplacement concept eliminates complex sealing arrangements by supporting the containers on pedestals composed of HCB blocks and filling the balance of the room void with HCB pellets.[16] This concept was developed for Opalinus clay, a very low permeability, saturated sedimentary rock.

In Canada, the approach to dealing with the perimeter regions in an emplacement room has focussed on the development of materials and placement technologies that can allow consistent and rapid placement of LBF materials to densities adequate to meet system performance requirements. A range of pneumatic-placement trials has been performed. Pneumatic placement has the advantage of ready application by remote-handling technologies at rapid rates and, if performed carefully, at consistent densities. A variety of materials have been examined for potential application as LBF and a number of placement trials have been performed.[10,11,13,14] Photographs taken at the URL during the some of these trials are presented as Figure 10.

Figure 9: Filling the Crown Regions of the Backfill and Plug Test at Äspö[15]

Figure 10: Light Backfill Pnuematic Emplacement Trials at AECL's URL

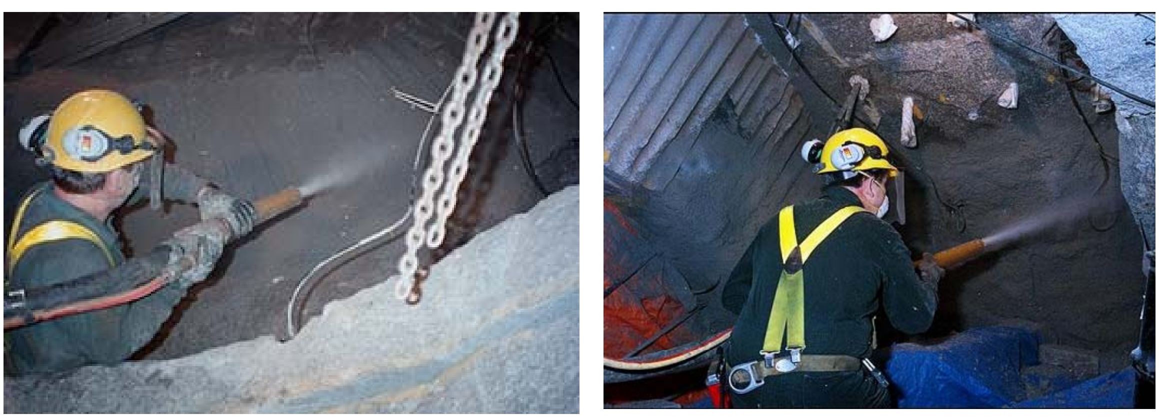


Figure 11: Application of Shotclay in the TSX and Backfill Wall

In addition to the trials directly associated with LBF placement, pneumatic placement was successfully developed and applied in the Tunnel Sealing Experiment (TSX) conducted at AECL's URL.[17,18] The "shotclay" materials in the TSX were used to fill the rough contact between the clay bulkhead blocks and the rock perimeter and to fill a region in a special backfill wall that could not otherwise be filled. Figure 11 shows this shotclay as it was placed within the clay-bulkhead key of the TSX and as part of the backfill wall. The results obtained in these emplacement trials are shown in Figure 12.

A variety of materials, ranging from 25 wt% to 70 wt% bentonite have been placed using pneumatic-placement technology. The densities attained in these trials were low relative to the HCB and buffer components of the sealing system but were sufficiently dense to provide constraint to the other sealing components. Further work to refine placement technologies and to improve densities for LBF are continuing as laboratory-based studies at AECL. The mechanical properties of these materials are being determined to ensure the ability to design and accurately predict the performance of a sealing system.

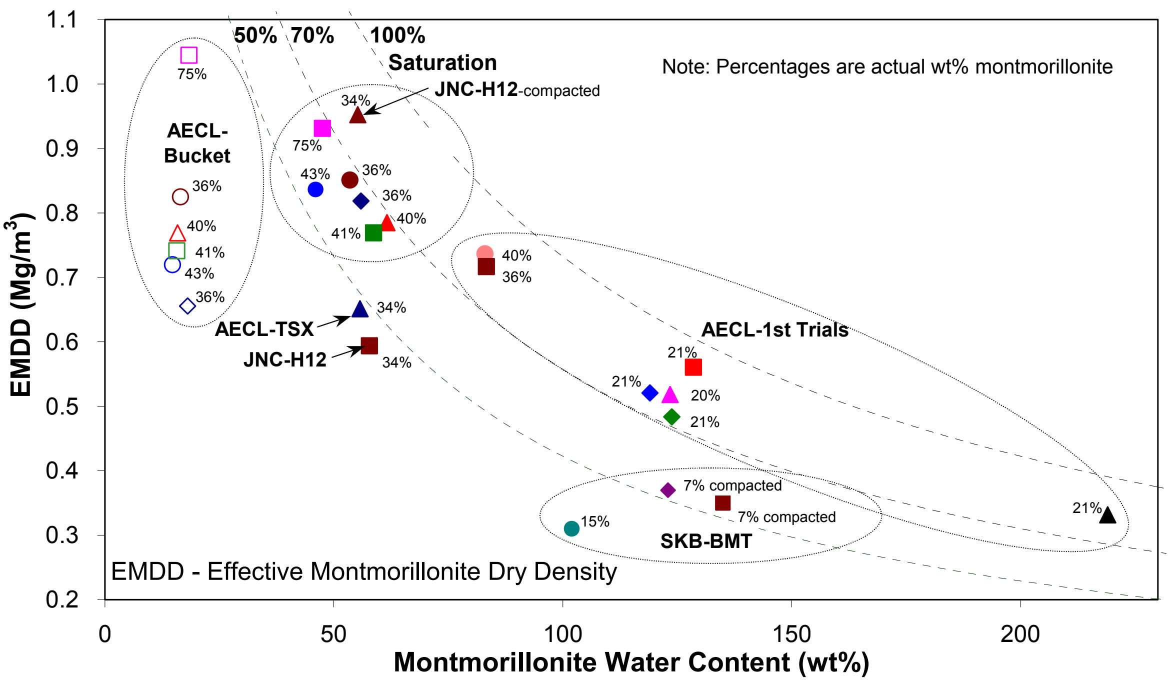


Figure 12: EMDDs Achieved in LBF Placement Trials [14]

III. SUMMARY

Gaps and voids created during the assembly of the sealing-system components and the emplacement of the used-fuel containers have the potential to adversely affect the thermal, hydraulic, mechanical and chemical performance of the engineered barriers. Potential gap-fill and light-backfill materials have been investigated to assess their practicability for use within a repository-sealing system. These gap fills and light backfills are required to minimize the reduction of the EMDDs for the major sealing components (i.e., HCB, buffer and DBF), particularly in the region immediately adjacent to the container to minimize the potential for microbial activity and MIC.

Technologies for placing these materials have been examined in the course of screening the materials and installation methods in repository-like conditions. Work is continuing towards improving the density of the GF and LBF materials and the consistency of their placement.

ACKNOWLEDGEMENTS

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