Potential Implications of Microbes and Salinity on the Design of Repository Sealing System Components

NWMO TR-2007-10 **November 2007**

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ABSTRACT

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Report No.: **NWMO TR-2007-10**
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Abstract

A study was undertaken to evaluate the potential impacts of microbial activity and salinity on the design of repository sealing system components, with an emphasis on the design of the bentonite buffer which would surround a used-fuel container in a deep geological repository. Laboratory experiments were conducted to study the effects of an in situ decrease in dry density in compacted MX-80 bentonite (from a starting dry density of 1.6 g/cm^3 to about 1.0 g/cm^3) on the aerobic microbial culturability, and hence microbial activity, in compacted bentonite under both low-salinity (distilled deionized water) and high-salinity (NaCl 100 g/L) conditions. The experiments were designed to simulate the effects of a bentonite-container placement gap in the design of a deep geological repository for used nuclear fuel under various conditions.

The present experimental results suggest that in a low-salinity environment, a high bentonite dry density of 1.6 g/cm^3 and the associated high swelling pressure are required in the design of a deep geological repository to suppress the microbial activity in compacted bentonite buffer surrounding the used-fuel containers. Therefore, in a low-salinity environment, it would be important to ensure that the design of bentonite dry density will be at or above the desirable as-placed density of 1.6 g/cm^3, both during the transient period of the resaturation process and at times when all sealing system components are equilibrated. The ability to achieve such a high as-placed bentonite dry density at all locations in the vicinity of used-fuel containers in a deep geological repository would be an important factor in the selection of a container placement method and repository design.

The present experimental results also suggest that in a high-salinity repository environment, salinity at or in excess of 100g/L will suppress the activity of indigenous microorganisms in the as-purchased MX-80 bentonite at or near the container surface. This appears to occur in bentonite with an as-placed dry density as low as about 1 g/cm^3. With salinity as the dominant factor for controlling microbial activity, the ability to achieve high as-placed dry bentonite densities would not be considered as an important factor for selecting a container placement method and hence repository design, in a high-salinity repository environment.

These experimental results are applicable for microbial activity indigenous to the as-purchased MX-80 bentonite. If saline-tolerant (halotolerant or halophilic) microorganisms were present or introduced into a deep geological repository, high as-placed dry bentonite densities may be required to suppress microbial activity.

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1. INTRODUCTION

1.1 BACKGROUND

A study was undertaken to evaluate the potential impacts of microbial activity and salinity on the design of repository sealing system components, with an emphasis on the design of the bentonite buffer which would surround a used-fuel container in a deep geological repository. Laboratory experiments were carried out with compacted Wyoming MX-80 bentonite plugs to determine the required value of compacted bentonite dry density around copper containers in a deep geological repository to minimize indigenous (i.e., as present in the as-purchased bentonite) microbial activity in this bentonite layer (Stroes-Gascoyne et al. 2006). These bentonite plugs were compacted (at 95% saturation) to a range of dry densities (0.8 - 2.0 g/cm^3), and infiltrated (under pressure) with sterile distilled deionized water or sterile NaCl solutions of 50 to 200 g NaCl/L. During the tests (duration 40 to 90 d), total pressure values were recorded. Upon termination, the bentonite plugs were analyzed for water content, water activity (a_w) and dry density. Swelling pressure values were calculated from total pressure data. Concurrent microbial analyses included culturing for heterotrophic aerobes, anaerobes and sulphate-reducing bacteria (SRB). Average pore size was measured on some samples using mercury intrusion porosimetry.

The physical measurements confirmed that a_w is a function of both dry density and porewater salinity, with the latter becoming the dominant control on a_w at high salinities (> 100 g/L). Swelling pressure values at given porewater salinity were low at dry density values of 0.8 and 1.3 g/cm^3, but increased significantly at dry density > 1.3 g/cm^3. An increase in porewater salinity caused a decrease in swelling pressure for a given dry density. The average pore diameter in bentonite samples with a dry density of 1.6 g/cm^3 appeared to increase slightly with increasing porewater salinity but remained unimodal and in the range of 0.01 to 0.02 µm. At dry densities of 0.8 and 1.3 g/cm^3 and porewater salinities of 0 and 50 g/L, culturability of heterotrophic aerobic bacteria increased by four orders of magnitude above back-ground levels in dry, as-bought bentonite (i.e., $(2.1 \pm 0.2) \times 10^2$ Colony Forming Units (CFU) per g dry bentonite). However, anaerobic heterotrophic bacteria and SRB did not increase significantly above background levels in any of the tests, presumably because the bentonite remained aerobic during the tests. At higher dry densities (1.6 to 2.0 g/cm^3) and higher porewater salinities (100 to 200 g/L) aerobic and anaerobic culturability remained at, or fell below, the background levels but in all combinations of dry density and porewater salinity tested, some culturability remained. It is hypothesized that these surviving organisms are either almost inactive, nearly dormant cells, or metabolically inactive spores. Aerobic culturability increased exponentially around $a_w \geq 0.96$ (corroborating earlier studies) but decreased sharply at swelling pressures of $\geq$ 2 MPa. Both a_w and swelling pressure are influenced by the dry density of the bentonite.

These results suggested that indigenous (i.e., naturally present) microbial activity in the bulk of compacted 100% bentonite in a low-salinity environment can be controlled as long as the placed bentonite has a (uniform) dry density $\geq$1.6 g/cm^3, which ensures that the swelling pressure is well above 2 MPa, a_w is well below 0.96 and the average pore size is < 0.02 µm. Observations from several natural bentonite deposits corroborate these results (Stroes-Gascoyne et al. 2006). Therefore, depending on the specific requirements identified, dry density (and hence swelling pressure and a_w) may be tailored in a low-salinity repository to provide a microbially unfavourable environment adjacent to the used fuel containers, ensuring that microbially influenced corrosion (MIC) is negligible. The results also suggested that in high-salinity environments (> 100 g/L) this high salinity is an important factor in suppressing indigenous microbial activity and that a high dry density is not required. However, this observation is applicable for indigenous microbial activity in compacted MX-80 bentonite. If saline-tolerant (i.e., halotolerant or halophilic) microorganisms were present, high bentonite dry densities may still be required to curtail microbial activity.

In a deep geological repository, it is likely that there will be a placement gap between the copper used fuel containers and the surrounding highly compacted bentonite buffer. Although this gap is expected to be small (in the order of about 5 cm) it could impact the dry density of the bentonite near the container for a period of time during the resaturation process of the bentonite. Initially the bentonite will become hot (maximum temperature typically < 100^{o}C) and will (partially) dry out and shrink away from the containers, as a result of the heat output of the used-fuel containers. However, it is unlikely that such heat and desiccation effects will be severe enough to eradicate microorganisms indigenous in the compacted bentonite. Some microorganisms could survive near the used-fuel container in almost dormant or spore form. Such presence constitutes a potential for increased microbial activity if conditions in the bentonite become more suitable for microbial activity. (A temporary or permanent reduction in bentonite dry density would constitute conditions more conducive to microbial activity).

When the used-fuel containers cool, the bentonite will cool as well and water (from the host rock) will be able to infiltrate the desiccated compacted bentonite and a slow resaturation process will occur. The expectation is that, as the bentonite resaturates, it will swell, such that the placement gap between the container and the buffer will be filled. It is also expected that over time, the bentonite will develop a uniform high dry density around the containers. However, there are several possibilities for the development of (temporary) lower-than-emplaced dry density in bentonite sealing materials in a repository during this resaturation period:

1. During resaturation, the bentonite near the container surface could swell into the placement gap and become (temporarily) less dense at the bentonite-container interface as a result the not-yet-equilibrated swelling process.

2. During resaturation, the water coming in from the host rock could push the compacted dried-out bentonite across the placement gap against the container such that bentonite dry density remains high at the container surface but would be reduced at the bentonite-host rock interface (i.e., at the water infiltration source).

3. A third possibility for the occurrence of bentonite with less than emplaced dry density in a repository would be at interfaces between sealing materials with different compositions. If, due to the difference in composition, one material develops a higher swelling pressure than the adjacent material, it would compress that other material, while becoming less dense itself.

Although it is expected that eventually the bentonite will have a uniform dry density in the repository, transition phases may create less dense bentonite and, therefore, an increased possibility of microbial activity. Stroes-Gascoyne et al. (2006) have shown that at and above a dry density of 1.6 g/cm^3, aerobic culturability is at or below background culturability in dry as-bought bentonite in a low-salinity environment. Therefore, a dry density of 1.6 g/cm^3 would be a minimum placement criterion for dry density in bentonite surrounding waste containers in a low-salinity repository.

Compacted bentonite could be placed differently in a repository, depending on the container placement concept chosen. Because this could affect the potential for maintaining as-placed dry density and, therefore, the likelihood of microbial activity, these used-fuel container placement conceptual designs are outlined in the next section.

1.2 CONTAINER PLACEMENT CONCEPTS

There are a number of used-fuel container placement options that could be applied in the development of deep geological repository (DGR) conceptual designs in crystalline rock and sedimentary rock.

a) In-Floor Borehole Placement Design Concept

In the in-floor borehole (IFB) placement design concept, the used-fuel container will be placed vertically into a borehole drilled into the floor of a placement room (Figure 1) (NUKEM 2003). The borehole is designed to receive one container. A portion of the highly compacted bentonite (HCB) is placed in the borehole as precompacted discs and rings, followed by the container and the balance of the highly compacted bentonite. The borehole is filled to the placement room floor with either additional highly compacted bentonite or other sealing system component materials, such as HCB gap fill or dense backfill. This is the reference placement method for the Swedish Nuclear Fuel and Waste Management Company (SKB) and Finnish Posiva Oy. As shown in Figure 1, there is a 5-cm-wide gap between the HCB buffer ring and the container.

b) Horizontal Borehole (KBS-3H) Placement Design Concept

The horizontal borehole placement design concept, KBS-3H, has been studied by the Swedish Nuclear Fuel and Waste Management Company (SKB) and the Finnish Posiva Oy as an alternative placement method (Figure 2) (Lindgren et al. 2003). This horizontal borehole (HBH) placement design concept uses a “super container” assembly comprising the used fuel container, a highly compacted bentonite sealing system component, and a perforated outer steel vessel. In this design concept, the bentonite rings are expected to be in close contact with the container and there will no physical gap between the bentonite rings and the container.

c) NAGRA In-room Placement Design Concept

The schematic diagram of the NAGRA-type in-room placement design concept is shown in (Figure 3). In this method, the used fuel container is placed on a highly compacted bentonite pedestal and the remaining voids in the room are filled with a highly compacted bentonite pellets (Johnson and King 2003). The pellets can be placed by direct placement or pneumatic methods. Upon placement, the bentonite material is expected to have an average dry density of 1.5 g/cm3 (Johnson and King 2003).

1.3 PURPOSE OF THIS REPORT

Previous work (Stroes-Gascoyne et al. 2006) established that at a dry density of $\geq$ 1.6 g/cm^3, indigenous aerobic culturability is at or below the background level (i.e., that found in dry as-bought MX-80 bentonite) at all salinities (up to 200 g/L) examined. At dry densities ≤ 1.3 g/cm^3, indigenous aerobic culturability has been found to increase significantly in low-salinity (<100 g/L) environments.

The purpose of the laboratory experiments described in this report was to examine the effects of an in situ decrease in dry density (from 1.6 to about 1.0 g/cm^3) on the microbial culturability in compacted bentonite plugs, under both low and high salinity conditions, to determine whether microbial culturability would be restored upon lowering of the dry density. The decrease in dry density was accomplished in the experiments by allowing the compacted bentonite to swell into an empty space at the top of the bentonite plugs (i.e., away from the water infusion source), to simulate the bentonite-container placement gap in a deep geological repository for used nuclear fuel.

2. MATERIALS AND METHODS

The microbial experiments carried out and described in this report involved bentonite plugs prepared following a standard laboratory procedure:

- The bentonite used was Wyoming MX-80 bentonite
- The bentonite was compacted into ethanol-sterilized pressure cells at a target dry density of 1.6 g/cm^3.
- The bentonite plugs were 20 mm high with a diameter of 16 mm.
- Before compaction, the bentonite was mixed with the infiltration solution such that after compaction (but before further infiltration) the bentonite would be at 95% saturation.
- The infiltration solutions consisted of sterilized, distilled deionized water or a solution of 100 g NaCl/L.

A total of eight bentonite plugs were prepared, all with a dry density of 1.6 g/cm^3. Four plugs were saturated to 95% with sterile distilled deionized water before compaction and four were saturated to 95% with a sterile 100 g NaCl/L solution. During the experiments, infiltration of the plugs with the sterile infiltration solutions continued (under pressure) and total pressures were measured, from which swelling pressures could be calculated.

Upon termination of any of these experiments, the bentonite plugs were sectioned into three parts (i.e., top, middle and bottom sections), which were analyzed for water content, a_w and dry density as well as cultured for heterotrophic aerobes, anaerobes and SRB. The methods for the physical measurements and culturing have been described by Stroes-Gascoyne et al. (2006) and included:

- The plugs (or plug sections) were weighed and measured to determine actual dry densities.
- Water activity (a_w) was measured on a subsample using a Decagon^{TM} WP4 Dewpoint PotentiaMeter (Decagon Devices, Pullman, WA).
- Water content was determined by subsequently drying this water activity subsample in an oven at 110^{o}C to constant weight.
- Aerobic and anaerobic heterotrophic bacteria were cultured on R2A medium (Reasoner and Geldreich 1985).
- Sulphate-reducing bacteria (SRB) were cultured on modified Postgate B medium (Atlas 1993).

All eight experiments were started on January 8, 2007. After 5 weeks (February 15, 2007), two experiments, one each with distilled water (experiment 1748) and 100 g NaCl/L infusion (experiment 1749) were terminated and the bentonite plugs (top, middle and bottom sections) were analyzed as described. The distilled deionized experiment 1748 was inadvertently compacted to a plug height of 30 mm instead of 20 mm, resulting in a dry density of about 1.07 g/cm^3, based on plug height and amount of material used. Experiment 1777 (started on February 23, 2007 and terminated on June 11, 2007) was a repeat of 1748, with the correct plug height (20 mm) and dry density (1.6 g/cm^3)

For the six remaining bentonite plugs (experiments 1772, 1783 and 1785 with distilled deionized water and experiments 1773, 1782 and 1784 with 100 g NaCl/L solution), the top restraints were adjusted (pulled up) slightly on February 14, 2007. Actual measurements of the amount of increase in plug height were made in March and a further adjustment occurred on April 2, 2007, because the initial adjustment resulted in a less than 5% (< 1 mm) increase in plug heights. The adjustment on April 2 resulted in an increase in plug height of about 11-17% (2.3 to 3.4 mm), with a calculated (expected) decrease in dry density in the remaining plugs from 1.6 g/cm^3 to about 1.40 $\pm$0.03 g/cm^3. The six adjusted plugs were allowed to take up water or saline solution (under pressure) and swell until May 23, when two tests, one each with distilled water (experiment 1772) and 100 g NaCl/L infusion (experiment 1773), were terminated. The bentonite plugs of these experiments (top, middle and bottom sections) were retrieved and analyzed as described.

The top restraints on the four remaining bentonite plugs (experiments 1783 and 1785 with distilled deionized water and experiments 1782 and 1784 with saline solution) were adjusted again, between 5 and 10 mm this time, which resulted in dry density reductions of 35% to 65% from the original 1.6 g/cm^3, i.e., to dry densities of approximately 1.2 to 1.0 g/cm^3. The tests were allowed to take up more water under pressure and were finally terminated on August 20, 2007 (experiments 1783 (distilled deionized water) and 1782 (saline solution)) or on August 22, 2007 (experiments 1785 (distilled deionized water) and 1784 (saline solution)).

3. RESULTS

Tables 1 and 2 contain results for plug height, dry density and swelling pressure, for the distilled deionized water and saline solution experiments, respectively. Plug height was measured accurately at the beginning and after each adjustment of each experiment. The dry density values in Tables 1 and 2 were determined or calculated by three methods: (i) from the measured plug height and the initial (target) dry density of 1.6 g/cm^3 during the test; (ii) from measured plug dimensions, total plug weight and average water content of the plugs (i.e., top, middle and bottom sections) at the end of the tests; and (iii) from the average water content of the plugs at the end of the tests assuming saturation and a specific gravity for bentonite of 2.70 g/cm^3.

Tables 3 and 4 contain the results for measured water contents, a_w and culturability (aerobes, anaerobes, SRB) in the top (T), middle (M) and bottom (B) segments of each plug, for the distilled deionized water and saline solution experiments, respectively.

Figure 4 gives the swelling pressure for experiment 1748 (distilled deionized water), the experiment that inadvertently had a plug height of 30 mm instead of 20 mm and has, therefore, a dry density of about 1.07 g/cm^3. Because of the plug height adjustments in the distilled deionized water experiments 1783 and 1785 to close to 30 mm, experiment 1748 can still serve as a comparison for those experiments.

Figures 4 to 12 show the swelling pressures occurring in the experiments as they were in progress. The swelling pressures were calculated from total pressure and input pressure data, which were gathered electronically continuously during each 24 h period. Every time a top restraint was adjusted, the pressure dropped to zero and built up again slowly, as the plug swelled into the empty space provided by the adjustment.

Figures 4 to 12 illustrate that in most experiments, the swelling pressure curve or curves (after adjustments) were still increasing, which implied that the experiments had not reached full swelling pressure but were still taking up water and developing equilibrium. It is also apparent that in the experiments with multiple adjustments to final plug heights of between 27 and 33 mm, the much lower swelling pressures later in the experiments appeared to take a long time to register and stabilize. It should be noted that the initial swelling pressure values in the distilled water experiments 1777, 1772, 1783 and 1785 (after 37 days at 1.6 g/cm^3) should all be at a similar value because all plugs were made with the same amount of bentonite and water and were compacted to a plug height of 20 mm. However, this appeared not to be the case; the swelling pressures for these experiments varied from 8300 to 3450 kPa after this period. By comparison, the data from corresponding experiments in Table 1 in Stroes-Gascoyne et al. (2006) (including those with dilute granitic groundwater) showed a spread in swelling pressure values of 7400 to 4550 kPa. For the saline (100 g NaCl/L) experiments (1749, 1773, 1782 and 1784) the swelling pressure at the start of the experiments (i.e., after 37 days at 1.6 g/cm^3) varied from 5000 to 3900 kPa, while by comparison the data from corresponding experiments in Table 1 of Stroes-Gascoyne et al. (2006) (including those with saline granitic groundwater) show a spread of 3350 to 1100 kPa (with one anomalously low value of 350 kPa).

Figure 13 shows the measured a_w values in each plug segment (of all experiments completed) plotted against measured water content. A comparison with Figures 4, and the data in Table 2 in Stroes-Gascoyne et al. (2006) shows that these values are in good agreement with data obtained previously.

Figure 14 shows the average a_w values in each plug (i.e., average of top, middle and bottom values in Figure 13 and Tables 3 and 4) as a function of dry density values, calculated with the three methods explained above. This graph shows that a_w values are below 0.96 for all saline experiments, and also below 0.96 for the distilled water experiment (1777) with a dry density of > 1.5 g/cm^3, but above a value of 0.96 for distilled deionized water experiments (1772, 1783 and 1785) with dry density values $\leq$ 1.4 g/cm^3. This is in agreement with data reported previously (i.e., in Figure 5, Stroes-Gascoyne et al. 2006).

Figure 15 shows the dry density in each experiment as calculated from the in situ measured plug height and the initial target dry density of 1.6 g/cm^3, versus the corresponding swelling pressure. As mentioned, there is a large spread in swelling pressure values for plugs with a target dry density of 1.6 g/cm^3. Possible reasons for this include:

(i) Full saturation has not yet been reached in these experiments (as corroborated partially by Figures 4 to 12);
(ii) The in situ dry density is in reality lower or higher than the target 1.6 g/cm^3 value;
(iii) The swelling pressure is affected as a result of any salt dissolving from the bentonite in the infusion solutions, especially in distilled deionized water; or
(iv) Non-uniform compaction of the plugs that has not yet been removed by the saturation and equilibration processes.

Figure 15 and Tables 1 and 2 show that swelling pressures are > 2MPa, for dry densities $\geq$ 1.54 g/cm^3, and largely < 2MPa for dry densities $\leq$ 1.44 g/cm^3. A swelling pressure > 2MPa has been found to keep indigenous aerobic culturability at or below background values (in dry as-bought bentonite) (Stroes-Gascoyne et al. (2006)). The results in Figure 15 are generally in good agreement with those reported in Figure 11 in Stroes-Gascoyne et al. (2006). One exception is the swelling pressure for experiment 1772, which was 2.1 MPa at a dry density of 1.40 g/cm^3. No reason is apparent for this slightly deviating result.

In Figure 16 aerobic culturability in all samples (as reported in Tables 3 and 4) is shown as a function of a_w values in those samples. At a_w values below 0.96, aerobic culturability is within a factor of two of background aerobic culturability in dry as-bought bentonite ($(2.1 \pm 0.2)\times10^2$ CFU/g). Some aerobic culture results in Figure 16 below an a_w value of 0.96 appear to be slightly higher than results previously obtained in comparable experiments (i.e., in Figure 16 in Stroes-Gascoyne et al. (2006)), especially those at a_w values < 0.96 for the 100 g NaCl/L experiments. Aerobic culturability in experiments with a_w values > 0.96, especially those at a_w values $\geq$ 0.99 on the contrary appear to be lower than previously found by as much as two orders of magnitude (i.e., around 10^4 CFU/g instead of 10^6 CFU/g).

Figure 17 shows aerobic culturability versus swelling pressure. The results in this figure are in good agreement with results obtained previously for similar experiments (i.e., Figure 20 in Stroes-Gascoyne et al. (2006)), with one exception. Aerobic culturability in experiment 1772 appears to be higher than expected (by about two orders of magnitude), considering this experiment had a swelling pressure of 2.1 MPa, at which pressure aerobic culturability is expected to be at or below background values, as apparent from Figure 20 in Stroes-Gascoyne et al. (2006). No reason is apparent for this deviating result.

In Figure 18, aerobic culturability (the average of top, middle and bottom results in each bentonite plug) is shown versus dry density (calculated from plug heights and initial target dry density). As noted above, the result from distilled water experiment 1772 (with a dry density of 1.40 g/cm^3) is again the only result not in agreement with previously obtained results, as shown in Figure 19 in which previous and current data are compared.

4. DISCUSSION

4.1 SUMMARY OF EXPERIMENTAL RESULTS

The expected swelling pressure for a bentonite plug fully saturated with distilled deionized water and with a dry density of 1.6 g/cm^3 would be about 7 to 8 MPa according to Figure 22 in Stroes-Gascoyne et al. (2006). However, the results obtained from the experiments described in the current study have shown a large spread in measured swelling pressures (e.g., Figure 15). Possible reasons for this include: (i) full saturation has not yet been reached in these experiments; (ii) the in situ dry density is in reality lower or higher than the target 1.6 g/cm^3 value; (iii) the swelling pressure is affected as a result of any salt dissolving from the bentonite in the infusion solutions, especially in distilled deionized water; or (iv) non-uniform compaction of the plugs that has not yet been removed by the saturation and equilibration processes.

From Figures 4 to 12 it is apparent that in most of these experiments, swelling pressure had not yet stabilized when the experiments were either adjusted or terminated. Therefore, the differences are at least partially caused by the time factor. However, it is also apparent from these figures that the ultimate swelling pressures (plateau values) in these experiments would not have stabilized at similar values. Therefore, swelling pressures are also affected by other factors, such as possibly slightly deviating dry density values, the difficult to assess dissolution of salt into the infusion water or the possibly uneven compaction throughout the plugs. However, the range of swelling pressure values measured in the distilled water experiments (1772, 1777, 1783 and 1785) with a dry density of 1.6 g/cm^3 (i.e., 8300 to 3450 kPa) are in reasonable agreement with values given in Figure 22 in Stroes-Gascoyne et al. (2006). This graph shows a wide scatter in swelling pressure values obtained in a variety of experiments, with a regression value of about 7 to 8 MPa for distilled deionized water at a dry density of 1.6 g/cm^3 (which corresponds to an effective montmorillonite dry density (EMDD) of 1.41 g/cm^3). In addition, Figure 15 shows that the swelling pressure in compacter MX-80 bentonite starts to increase exponentially at a dry density value between 1.4 and 1.6 g/cm^3. The range of swelling pressures obtained in the current saline experiments (1749, 1773, 1782, 1784) (i.e., 5000 to 1100 kPa with one anomalously low value of 350 kPa) are also largely in the range of values shown for a porewater salinity of 100g/L and a dry density of 1.6 g/cm^3 (or EMDD of 1.41 g/cm^3) in Figure 22 of Stroes-Gascoyne et al. (2006). The regression value derived from this graph for the swelling pressure of compacted bentonite at a porewater salinity of 100g/L and EMDD of 1.41 g/cm^3 appears to be about 2.5 to 3 MPa.

In most experiments, the bottom (B) segment of each plug had the highest water content (Tables 3 and 4). This is expected because the water enters the plugs at the bottom. The fact that the moisture content is not uniform throughout the plugs indicates that the plugs had not yet developed a uniform dry density or swelling pressure and that such a development would be a long process. The larger the plug height adjustment, the more varied the water content in the different parts of the plugs. The fact that in most adjusted experiments the water content in the top (T) is the lowest suggests that there is no, or very little, water transport along the pressure cell wall – bentonite interface.

The measurements that are likely most accurate in these experiments are moisture content and a_w (Figure 13) because they require small amounts of sample and more importantly, were determined on the same sample (Section 2). Dry density values are more problematic and show a spread between the three different methods used to obtain these values (Tables 1 and 2 and Figure 14). The most accurate dry density values likely are the ones calculated from measured plug height and the assumption that initial target dry density of 1.6 g/cm^3 was correct. The second method uses the total weight of each plug (which can be measured accurately) but depends on averaging moisture content data from the top, middle and bottom segments of each plug. These segments likely did not have exactly the same volume, which would bias averaging towards the segment with the largest volume. The third method also uses average water content, and assumes saturation in each segment of the plug, which likely is an incorrect assumption. Nevertheless, the results shown in Figure 14 for average a_w values generally corroborate results obtained previously.

The objective of these experiments was to determine if a decrease in dry density from values at which microbial culturability is limited to, or below, background culturability in dry as-bought bentonite, would increase if dry density were to decrease. Dry density decrease would result from expansion of the bentonite, in this case into an empty space, representing the expected empty placement gap around a container in a repository. Figure 16 illustrates that a_w values need to be above 0.96 for aerobic culturability to increase significantly above background values (as found previously by Stroes-Gascoyne et al. (2006). Even for experiment 1772, for which the aerobic culturability in the top, middle and bottom parts of the bentonite plug appears to be too high (based on dry density and swelling pressure measurements for this experiment) by at least an order of magnitude, a_w values are well above 0.96.

Figure 18 shows that at a dry density of 1.6 g/cm^3, aerobic culturability (averaged per plug) is at or below background culturability in dry as-bought bentonite (i.e., $(2.1 \pm 0.2)\times10^2$ CFU/g), as previously established, for both distilled deionized water and 100 g NaCl/L infusion solutions. Upon a decrease in dry density to as low as 1.16 g/cm^3 and 1.10 g/cm^3 in the distilled deionized water experiments 1783 and 1785, respectively, aerobic culturability increased to about 10^4 CFU/g in the bottom segment of experiment 1785 (Table 3), an increase of two orders of magnitude, but for experiment 1783, an increase above background values did not occur. There is no plausible explanation for the difference in these two experiments, because they were basically duplicate experiments except for a slight difference in dry density. Previous work has shown that at dry densities of 0.8 and 1.3 g/cm^3, aerobic culturability would be in the order of 10^6 to 10^7 CFU/g and 10^4 CFU/g, respectively, as shown in Figure 19 in Stroes-Gascoyne et al. (2006). Therefore, at a dry density of about 1.1 g/cm^3, the aerobic culturability values found for experiments 1748 and 1785 are in good agreement with (or perhaps slightly lower than) expected values, as shown in Figure 19. However, the aerobic culture results for experiment 1772 are higher than expected (by at least one order of magnitude) and lower than expected in experiment 1783 (by two orders of magnitude). Interpretation of these results is difficult, although since both experiment 1772 and 1785 show an increase in aerobic culturability, these results, although not unanimous, suggest that microbial culturability may recover from the effects of high dry densities and thus high swelling pressures for samples with infusion of distilled deionized water.

As shown in Figure 18 and Table 4, the aerobic culture results for all experiments with saline (100 g/ NaCl/L) solution infusion indicate that the microbial culturability is limited to, or slightly below, the background culturability of dry as-bought bentonite. The dry densities of these samples range from 0.98 to 1.73 g/cm^3. The results indicate that the indigenous aerobic culturability would be maintained at low levels in the presence of highly saline porewater and is not affected by the decrease of the dry density, corroborating previous results (Stroes-

Gascoyne et al. 2006). Indigenous anaerobic and SRB culturability remained at background levels in most experiments, although there appears to be a slight increase in SRB numbers in the experiments with the longest duration (> 220 d, i.e., more than twice as long as the longest experiments reported in Table 2 in Stroes-Gascoyne et al. (2006)) and the lowest dry densities. Low levels of SRB and anaerobes have been observed before and are attributed to the fact that the plugs did not develop conditions that were anaerobic enough to encourage anaerobic organisms to thrive. It would probably require a long time period for bentonite (of low enough dry density to allow aerobic activity) to become fully anaerobic, due to the low nutrient content in bentonite, which slows oxygen reduction by microbes.

4.2 POTENTIAL IMPLICATION FOR THE DESIGN OF THE SEALING SYSTEM AROUND THE CONTAINER

The experimental results discussed in this report have potential implications for the various container placement and sealing systems designs considered for a deep geological repository. These implications will be discussed below. However, the results obtained from these microbial experiments are applicable for microorganisms indigenous to the MX-80 bentonite. Should a different bentonite be considered for sealing systems, or should MX-80 bentonite contain non-indigenous microorganisms (e.g., introduced from elsewhere), the possibility exists that microorganisms will be present that have tolerance characteristics that are different from indigenous MX-80 microorganisms. Therefore, the following discussion is applicable for microorganisms indigenous to “as-bought” MX-80 bentonite.

4.2.1 Low-Salinity Repository Environment

The experiments with distilled deionized water infusion appear to indicate that under low-salinity (<100 g/L) repository conditions, microbial culturability (and hence activity), indigenous to the as-bought bentonite, at or near the used-fuel container surface would be determined primarily by the bentonite dry density around the container. At an as-placed dry density of 1.6 g/cm^3, the aerobic culturability is at or below background levels.

At locations in a repository where the bentonite is allowed to swell, its dry density would decrease and indigenous microbial culturability could increase by several orders of magnitude, depending on the extent of swelling. It appears, therefore, necessary to maintain a uniform high dry density throughout the compacted bentonite materials that would surround the used-fuel containers in a deep geological repository, to suppress microbial activity and reduce the potential for MIC to an insignificant level.

In order to minimize the microbial activity at or near the container surface in a low-salinity repository environment, it is, therefore, important to place the bentonite buffer with as-placed dry densities as high as practically possible to ensure that the bentonite dry density is at or above 1.6 g/cm^3 at all locations in the vicinity of the containers during the transient period of the resaturation process. This will also ensure that the equilibrated bentonite dry density remains at or above the required minimum dry density of 1.6 g/cm^3 throughout the latter stages of a fully saturated repository.

a) In-floor Borehole Placement Design

For the in-floor borehole placement design, the as-placed dry density of the highly compacted bentonite (HCB) rings and discs should be as high as possible (i.e., > 1.6 g/cm^3). The as-placed dry density of the bentonite gap fill in the region between the HCB bentonite and the container also should be as high as possible (i.e., as close as possible to 1.6 g/cm^3.)

b) Horizontal Borehole (KBS-3H) Placement Design

For the horizontal borehole (KBS-3H) placement design, the HCB buffer is designed to be in close contact with the container and there should be no significant physical gap between the bentonite buffer and the container. A high as-placed dry density (i.e., > 1.6 g/cm^3) of the HCB buffer should be applied.

c) NAGRA In-room Placement Design

For the NAGRA in-room placement design, the container is to be placed on a HCB pedestal. The remaining space in the placement tunnel is to be filled with bentonite pellets and fines. As mentioned previously, NAGRA expect that an average dry density of about 1.5 g/cm^3 can be realized for the pellet fill in this space. However, for a low salinity environment, this density is slightly below the minimum as-placed dry density of 1.6 g/cm^3 required to minimize microbial activity at or in the vicinity of the container. There may also be regions of the placement tunnel with a dry density lower than 1.5 g/cm^3, which may allow an increase in microbial activity above background levels. Therefore, for low salinity-repository environments incorporating an in-room container placement design, there is a need to improve the placement method of pellet fill and to demonstrate that an as-placed dry density of 1.6 g/cm^3 or higher can be achieved for placement tunnel bentonite pellet fill.

4.2.2 High-Salinity Repository Environment

In a high-salinity repository environment (e.g., as high or higher than the NaCl concentration of 100 g/L used in this study), such high porewater salinity will minimize the microbial culturability and activity by reducing the water activity (a_w) to less than the threshold level of around 0.96. The current experimental findings indicate that such a highly saline environment is capable of suppressing the microbial culturability and activity in a wide range of bentonite dry densities from 0.98 to 1.73 g/cm^3.

In a high-salinity repository environment, the microbial experimental results suggest that there would be no need to place highly compacted bentonite sealing materials with an as-placed dry density ≥ 1.6 g/cm^3 in order to minimize microbial activity since this activity is now controlled mainly by the highly saline porewater and the resulting low a_w values.

However, bentonite buffer components with reasonably high as-placed dry densities may still be desirable in order to complement the salinity effects on microbial activity. A high dry density would continue to suppress microbial activity even in the unlikely event that the indigenous microorganisms gradually would develop a tolerance for, or adaptation to, high salinity over time. Such adaptations require minimum levels of metabolism and replication, and the continued presence of high dry densities in addition to high salinity would further reduce the possibility of developing such tolerance. In addition, a high dry density environment would ensure smaller pore spaces, which would prevent the migration of salinity-tolerant microorganisms from elsewhere.

a) In-floor Borehole Placement Design

Under highly saline repository conditions, an as-placed gap fill dry density as low as 1 g/cm^3 would likely be sufficient to minimize the microbial activity at or near the container surface. No further placement development efforts are required to achieve such low as-placed dry densities. However, it would still be desirable to achieve an as-placed dry density of gap fill as high as practically possible, for reasons discussed above.

b) Horizontal Borehole (KBS-3H) Placement Design

It is expected that the high salinity together with the HCB buffer in this design (i.e., no gap fill) will work very well to minimize microbial activity at and near the container surface.

c) NAGRA In-room Placement Design

Under the highly saline repository environments, the as-placed dry density of the bentonite pellets (near 1.5 g/cm^3) will likely be sufficient to suppress the microbial activity near or at the container surface. Such dry densities for pellet placement have been demonstrated.

4.2.3 The Potential Introduction or Occurrence of Halotolerant or Halophilic Microorganisms in Sealing Materials

Salt-tolerant or salt-loving (i.e., halotolerant or halophilic) microorganisms have been found to be active in highly saline (almost saturated) environments. Some examples are the microbial populations found in Great Salt Lake (Utah), the Dead Sea (Israel) and certain man-made environments such as marine salterns (i.e., evaporation pools for the commercial production of salt from sea water). A detailed review of Halobacteriaceae and specific responses to high-salt environments in non-Halobacteriaceae can be found in Meike and Stroes-Gascoyne (2000).

In addition to granitic rock formations, Ordovician sedimentary deposits are considered currently in Canada as potential host rock candidates for the future location of a repository. These Ordovician sedimentary deposits, both shales and limestones, have been found to contain highly saline groundwater. These sedimentary deposits would need to be studied to determine if they contain microorganisms adapted to high salinity.

5. CONCLUSIONS

The present experimental results indicate that in a low-salinity (NaCl concentration <100 g/L) environment, high bentonite dry densities (≥ 1.6 g/cm^3) and the associated high swelling pressures are required to suppress the indigenous microbial activity in compacted bentonite buffer at or near the container surface in a deep geological repository. The bentonite blocks, rings and discs should have as-placed dry density as high as practically achievable (> 1.6 g/cm^3). The gap fill bentonite should also have an as-placed density as close possible to 1.6 g/cm^3. This will ensure that the bentonite dry density will be at or above the desirable as-placed dry density of 1.6 g/cm^3 both during the transient period of the resaturation process and at later times when all sealing system components are equilibrated.

In a high-salinity (e.g., NaCl concentration ≥100 g/L) environment, the high groundwater and thus porewater salinity will be capable of suppressing the indigenous microbial activity at or near the container surface in MX-80 bentonite with an as-placed dry density as low as about 1 g/cm^3. With salinity as the dominant factor for controlling microbial activity, the ability to achieve high as-placed dry bentonite densities is not considered to be as an important factor for selecting a container placement method and hence repository design in a high-salinity repository environment.

These conclusions are applicable for microorganisms indigenous to MX-80 bentonite only. The potential implications of introducing halo-tolerant (salt-tolerant) or halophilic (salt-loving) microorganisms into bentonite sealing materials would need to be studied further.

6. RECOMMENDATIONS

Microbial investigations will be required to assess the presence of halo-tolerant or halophilic microorganisms in Ordovician sedimentary rock formations and to assess whether the in situ high groundwater salinity is suppressing the activity of these bacteria. As well, the potential migration of halo-tolerant or halophilic microorganisms through dessication cracks or interface pathways in the bentonite rings and blocks during the resaturation process for a deep geological repository would also need to be studied.

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Table 1: Physical Data for Bentonite Plug Swelling Experiments with Distilled Deionized Water Infusion

Start Date (2007)	End Date (2007)	Interval Time (d)	Plug Height (mm)	Dry Density g/cm^3			Swelling Pressure (kPa)
				C_1	C_2	C_3	
Experiment 1748							
Jan. 08	Feb. 15	37	30.0**	1.07	1.00	1.03	845
Experiment 1777 (Repeat of 1748)							
Feb. 23	Jun. 11	108	20.0	1.60*	1.50	1.65	8296
Experiment 1772							
Jan. 08	Feb. 14	37	20.0	1.60*	n/a	n/a	5850
Feb. 14	Apr. 02	48	20.38	1.57	n/a	n/a	4762
Apr. 02	May 23	51	22.88	1.40	1.32	1.31	2125
Experiment 1783							
Jan. 08	Feb. 14	37	20.0	1.60*	n/a	n/a	3448
Feb. 14	Apr. 02	48	20.13	1.59	n/a	n/a	2510
Apr. 02	May 24	52	22.29	1.44	n/a	n/a	1320
May 24	Aug. 20	88	27.47	1.16	1.05	1.05	148
Experiment 1785							
Jan. 08	Feb. 14	37	20.0	1.60*	n/a	n/a	3996
Feb. 14	Apr. 02	48	20.06	1.595	n/a	n/a	3155
Apr. 02	May 24	52	23.38	1.37	n/a	n/a	1237
May 24	Aug. 22	90	29.13	1.10	0.98	0.97	727

C_1 = Calculated from plug height and initial (target) dry density (1.60 g/cm^3)
C_2 = Calculated from average water content, assuming saturation and specific gravity bentonite = 2.70 g/cm^3
C_3 = Measured from total plug dimensions, weight and average ((T+M+B)/3) water content (end of test)
* = Initial (target) value of 1.60 g/cm^3 assumed to be correct
** = Plug height 30 mm, experiment repeated (1777)
n/a = not applicable
T,M,B = Top, Middle, Bottom of clay plugs

Table 2: Physical Data for Bentonite Plug Swelling Experiments with Saline (100 NaCl/L) Solution Infusion

Start Date (2007)	End Date (2007)	Interval Time (d)	Plug Height (mm)	Dry Density g/cm^3 C_1	Dry Density g/cm^3 C_2	Dry Density g/cm^3 C_3	Swelling Pressure (kPa)
Experiment 1749							
Jan. 08	Feb. 15	38	20.0	1.60*	1.62	1.73	4977
Experiment 1773							
Jan. 08	Feb. 14	37	20.0	1.60*	n/a	n/a	4161
Feb. 14	Apr. 02	48	20.36	1.57	n/a	n/a	2482
Apr. 02	May 23	51	22.54	1.42	1.46	1.48	142
Experiment 1782							
Jan. 08	Feb. 14	37	20.0	1.60*	n/a	n/a	4524
Feb. 14	Apr. 02	48	20.15	1.59	n/a	n/a	2874
Apr. 02	May 24	52	22.51	1.42	n/a	n/a	632
May 24	Aug. 20	88	26.90	1.19	1.22	1.17	198
Experiment 1784							
Jan. 08	Feb. 14	37	20.0	1.60*	n/a	n/a	3917
Feb. 14	Apr. 02	48	20.83	1.54	n/a	n/a	2632
Apr. 02	May 23	51	22.66	1.41	n/a	n/a	715
May 23	Aug. 22	91	32.81	0.98	1.04	1.15	196

C_1 = Calculated from plug height and initial (target) dry density (1.60 g/cm^3)
C_2 = Calculated from average water content, assuming saturation and specific gravity bentonite = 2.70 g/cm^3
C_3 = Measured from total plug dimensions, weight and average ((T+M+B)/3) water content (end of test)
* = Initial (target) dry density of 1.60 g/cm^3 assumed to be correct
n/a = not applicable
T,M,B = Top, Middle, Bottom of clay plugs

Table 3: Culture Data for Bentonite Plug Swelling Experiment with Distilled Deionized Water Infusion

Experiment	Duration (d)	Dry Density C_1 C_2 C_3 (g/cm^3)	Water Content (%)	a_w	Swelling Pressure (end) (kPa)	Aerobes (CFU/g)	Anaerobes (CFU/g)	SRB (MPN/g)
1748	37	1.07,1.00,1.03			845			
T			47.35	0.991		$(4.43\pm0.80)x10^{2}$	$(6.25\pm4.64)x10^{1}$	13.4
M			52.60	0.995		$(2.56\pm0.32)x10^{3}$	$(6.69\pm1.05)x10^{1}$	< 5.7
B			87.69	0.996		$(1.61\pm0.17)x10^{4}$	$(5.85\pm1.53)x10^{2}$	6.9
1777(1748R)	108	1.60,1.50,1.65			8296			
T			29.41	0.950		$(1.25\pm0.76)x10^{2}$	contaminated	8.5
M			27.37	0.944		$(1.44\pm0.54)x10^{2}$	$(4.45\pm2.01)x10^{2}$	< 4.2
B			32.16	0.957		$(9.75\pm3.81)x10^{1}$	$(9.75\pm3.81)x10^{1}$	6.6
1772	136	1.40,1.32,1.31			2125			
T			34.98	0.973		$(2.12\pm0.08)x10^{4}$	$(1.55\pm0.51)x10^{2}$	5.3
M			35.98	0.977		$(2.61\pm0.60)x10^{4}$	$(4.74\pm1.58)x10^{1}$	< 4.9
B			44.67	0.986		$(2.19\pm0.20)x10^{4}$	$(4.75\pm1.18)x10^{1}$	7.3
1783	225	1.16,1.05,1.05			148			
T			53.10	0.994		$(2.65\pm1.90)x10^{2}$	$(5.17\pm4.03)x10^{1}$	6.0
M			54.84	0.994		$(1.49\pm1.57)x10^{2}$	$(1.42\pm0.62)x10^{2}$	7.7
B			65.78	0.994		$(9.04\pm4.03)x10^{1}$	$(1.68\pm1.07)x10^{2}$	< 5.8
1785	227	1.10,0.98,0.97			727			
T			55.47	0.993		$(1.14\pm0.35)x10^{3}$	$(1.23\pm1.20)x10^{2}$	20.2
M			62.96	0.994		$(1.46\pm0.20)x10^{3}$	$(9.27\pm0.40)x10^{1}$	7.2
B			76.92	0.995		$(2.19\pm0.22)x10^{4}$	$(4.64\pm2.32)x10^{1}$	9.1

C_1 = Calculated from plug height and initial (target) dry density (1.60 g/cm^3)
C_2 = Calculated from average water content, assuming saturation and specific gravity bentonite = 2.70 g/cm^3
C_3 = Measured from total plug dimensions, weight and average ((T+M+B)/3) water content
T, M, B, = Top, Middle, Bottom part of plug

Table 4: Culture Data for Bentonite Plug Swelling Experiment with Saline (100g NaCl/L) Solution Infusion

Experiment	Duration (d)	Dry Density C_1 C_2 C_3 (g/cm^3)	Water Content (%)	a_w	Swelling Pressure (end) (kPa)	Aerobes (CFU/g)	Anaerobes (CFU/g)	SRB (MPN/g)
1749	38	1.60,1.62,1.73			4977			
T			25.07	0.830		(1.22±0.19)x10^{2}	(1.68±2.91)x10^{1}	< 3.9
M			23.64	0.820		(1.61±0.43)x10^{2}	(1.21±0.17)x10^{2}	< 5.3
B			25.68	0.824		(2.12±0.12)x10^{2}	(8.20±7.10)x10^{1}	< 6.4
1773	136	1.42,1.46,1.48			142			
T			32.58	0.915		(8.34±4.25)x10^{1}	(9.81±0.85)x10^{1}	< 4.6
M			30.74	0.913		(2.10±0.35)x10^{2}	(1.54±0.67)x10^{2}	< 3.8
B			31.34	0.917		(3.10±0.99)x10^{2}	(6.25±0.00)x10^{1}	5.9
1782	225	1.19,1.22,1.17			198			
T			34.36	0.931		(8.72±2.35)x10^{1}	(3.33±0.54)x10^{2}	< 4.8
M			39.60	0.932		(2.18±0.88)x10^{2}	(1.33±1.21)x10^{2}	14.8
B			61.11	0.937		(8.05±5.68)x10^{1}	(8.05±5.68)x10^{1}	6.7
1784	227	0.98,1.04,1.15			196			
T			39.83	0.933		(1.34±0.50)x10^{2}	(8.92±4.21)x10^{1}	< 5.2
M			50.22	0.935		(2.67±0.90)x10^{2}	(8.21±2.05)x10^{1}	7.4
B			88.30	0.939		contaminated	(5.55±2.41)x10^{1}	10.3

C_1 = Calculated from plug height and initial (target) dry density (1.60 g/cm^3)
C_2 = Calculated from average water content, assuming saturation and specific gravity bentonite = 2.70 g/cm^3
C_3 = Measured from total plug dimensions, weight and average ((T+M+B)/3) water content
T,M,B = Top, Middle, Bottom part of plug

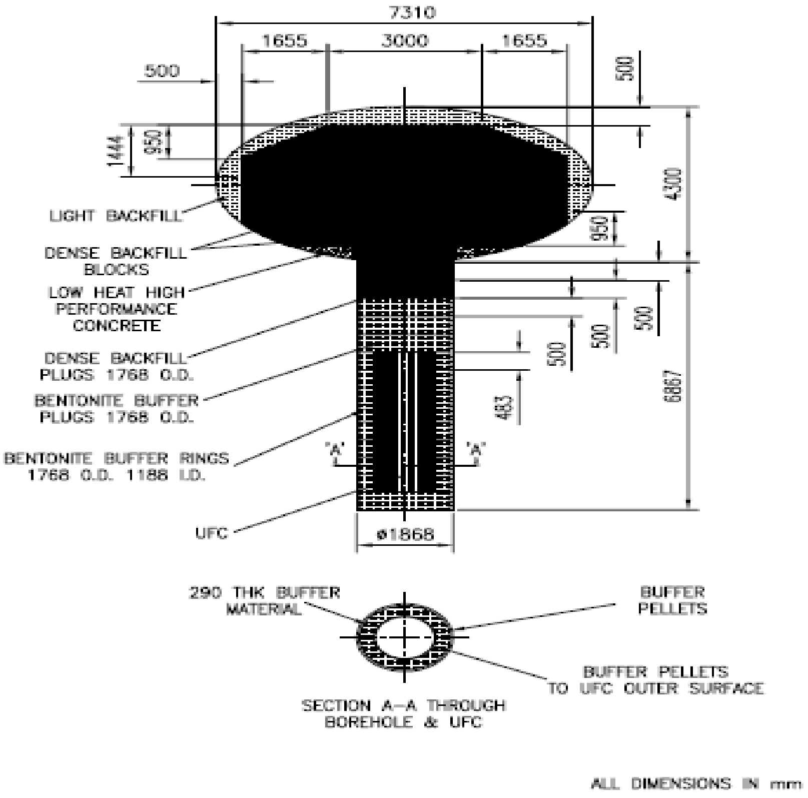

Figure 1: In-floor Borehole Placement Design Concept

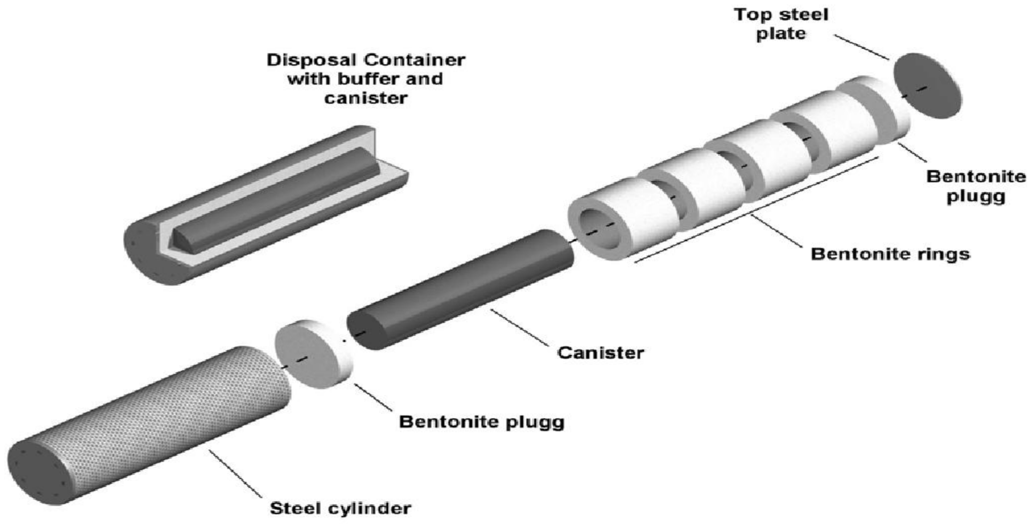

Figure 2: The Supercontainer Package Employed in the Horizontal Borehole Placement (KBS-3H) Design Concept

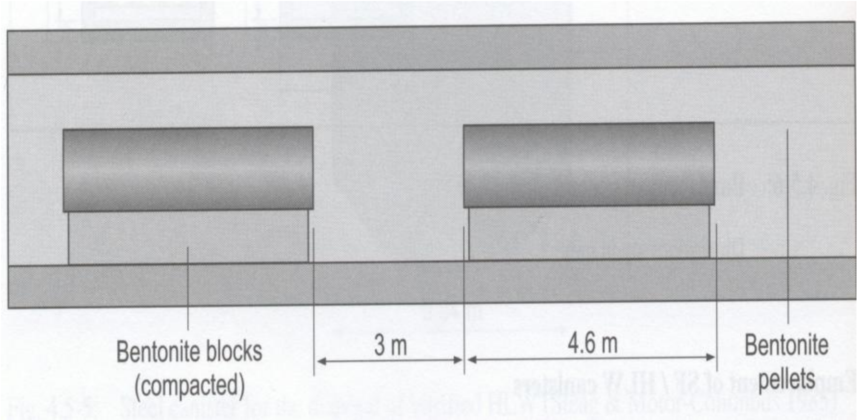

Figure 3: NAGRA In-room Placement Design Concept

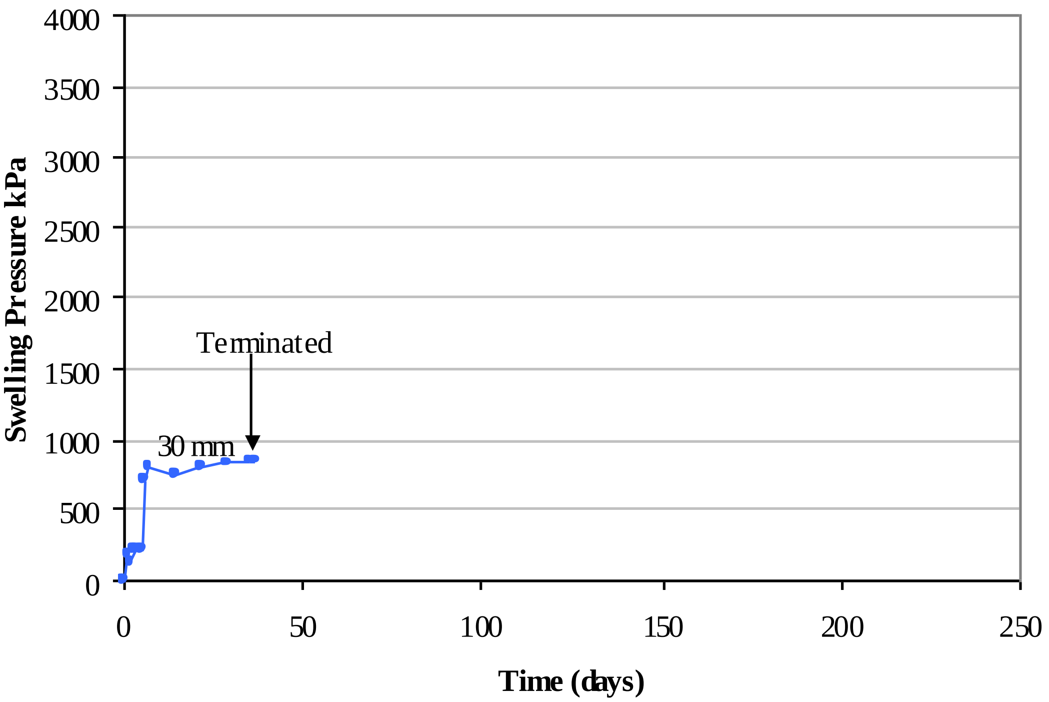

Figure 4: Swelling Pressure as a Function of Time in Experiment 1748 (bentonite dry density 1.07 g/cm^3) with Distilled Deionized Water Infusion

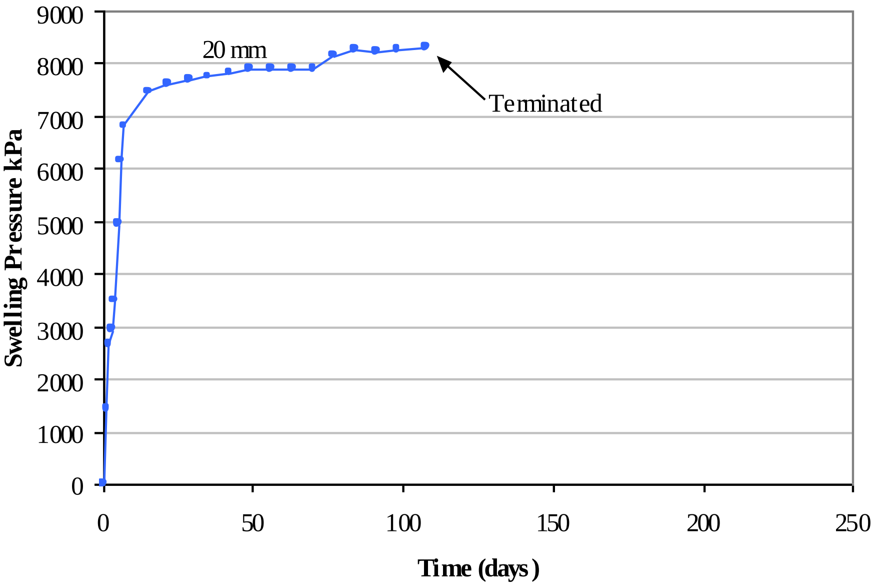

Figure 5: Swelling Pressure as a Function of Time in Experiment 1777 (bentonite dry density 1.60 g/cm^3) with Distilled Deionized Water Infusion

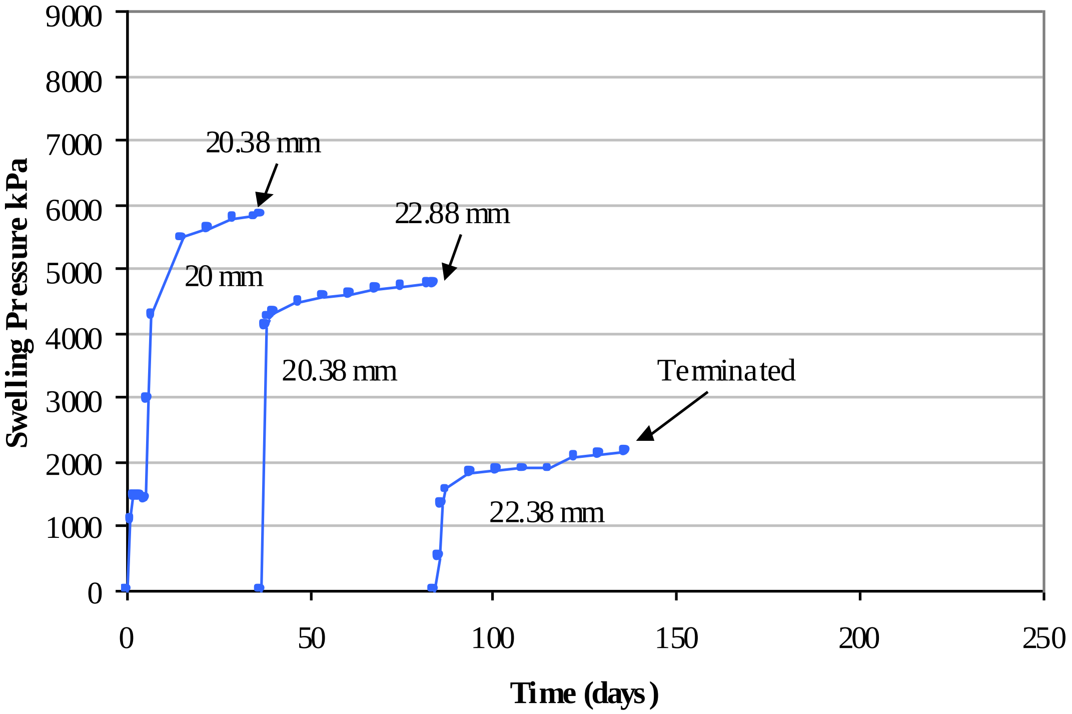

Figure 6: Swelling Pressure as a Function of Time in Experiment 1772 (bentonite dry density 1.60, 1.57 and 1.40 g/cm^3) with Distilled Deionized Water Infusion

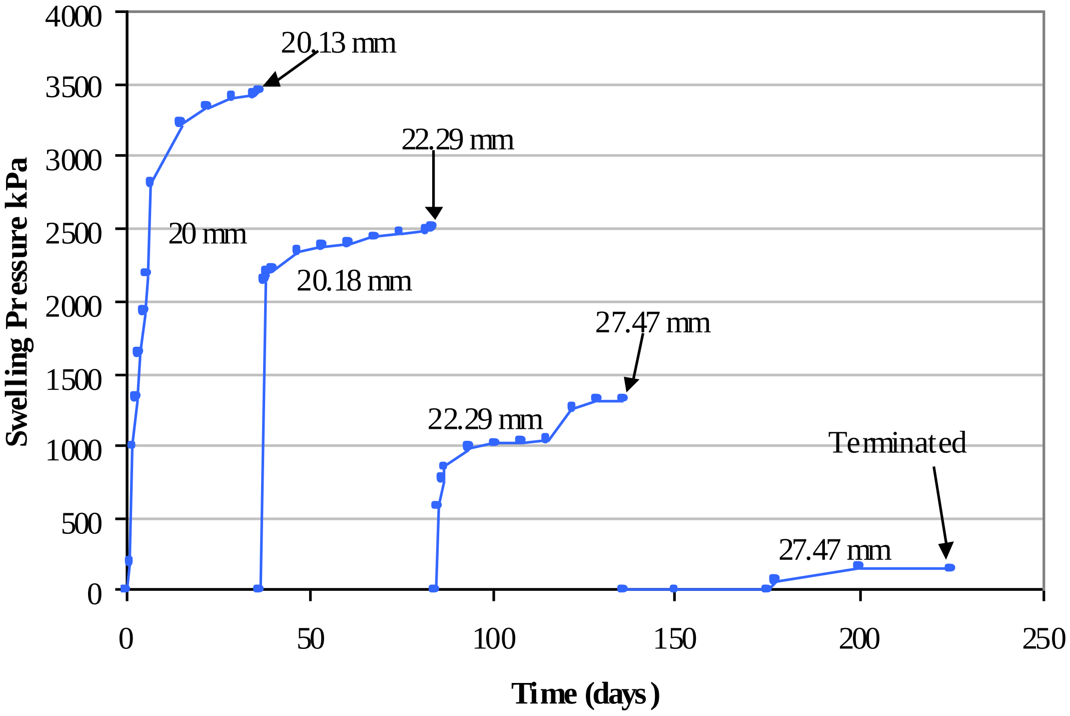

Figure 7: Swelling Pressure as a Function of Time in Experiment 1783 (bentonite dry density 1.60, 1.59, 1.44 and 1.16 g/cm^3) with Distilled Deionized Water Infusion

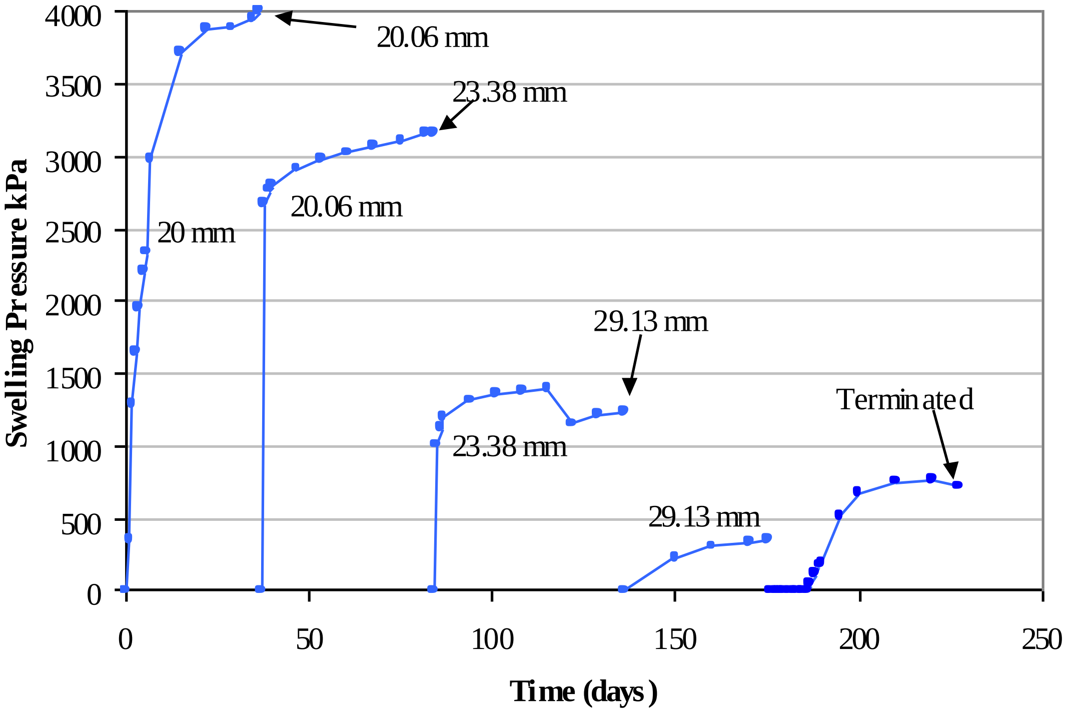

Figure 8: Swelling Pressure as a Function of Time in Experiment 1785 (bentonite dry density 1.60, 1.595, 1.37 and 1.10 g/cm^3) with Distilled Deionized Water Infusion

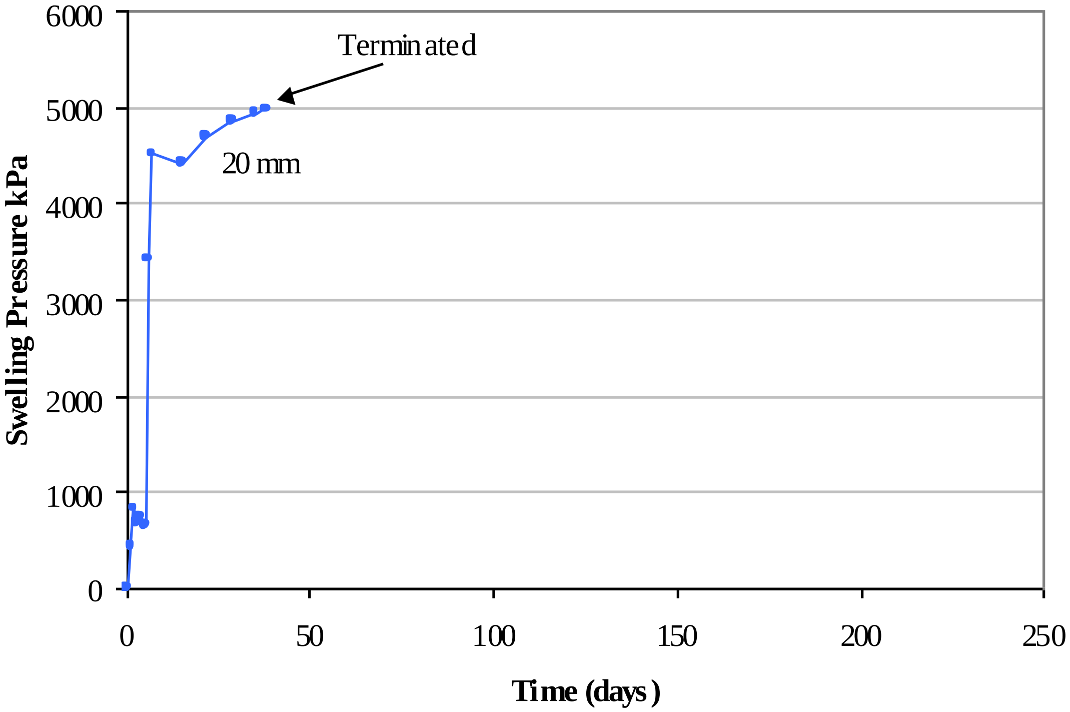

Figure 9: Swelling Pressure as a Function of Time in Experiment 1749 (bentonite dry density 1.60 g/cm^3) with 100 g NaCl/L Infusion

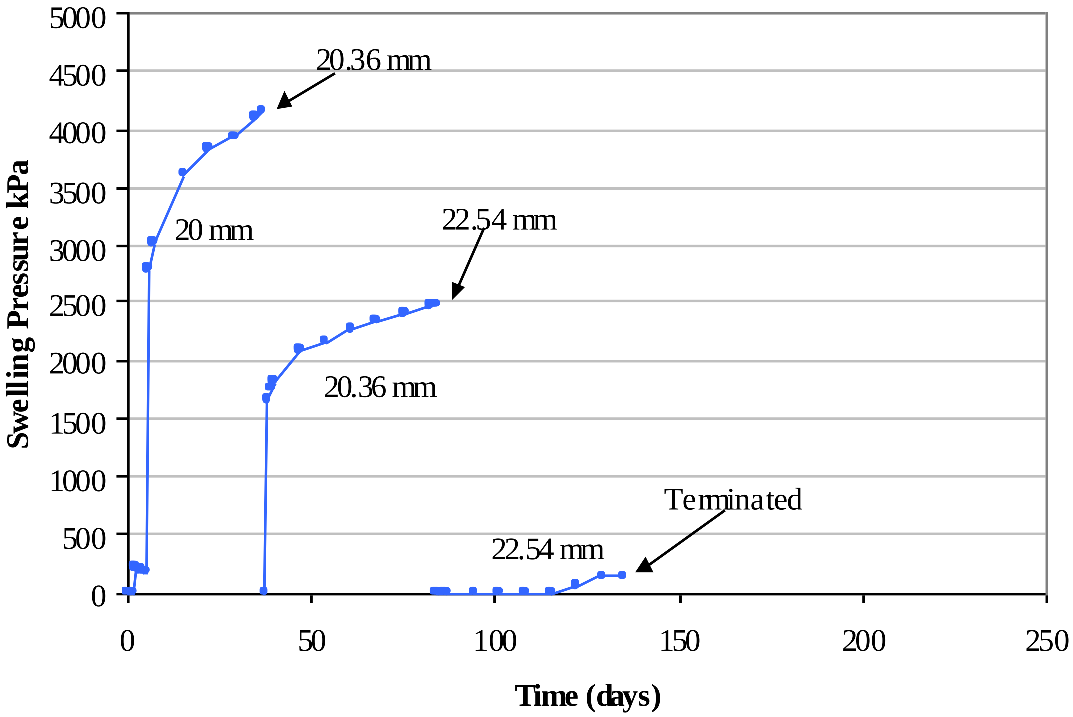

Figure 10: Swelling Pressure as a Function of Time in Experiment 1773 (bentonite dry density 1.60, 1.57 and 1.42 g/cm^3) with 100 g NaCl/L Infusion

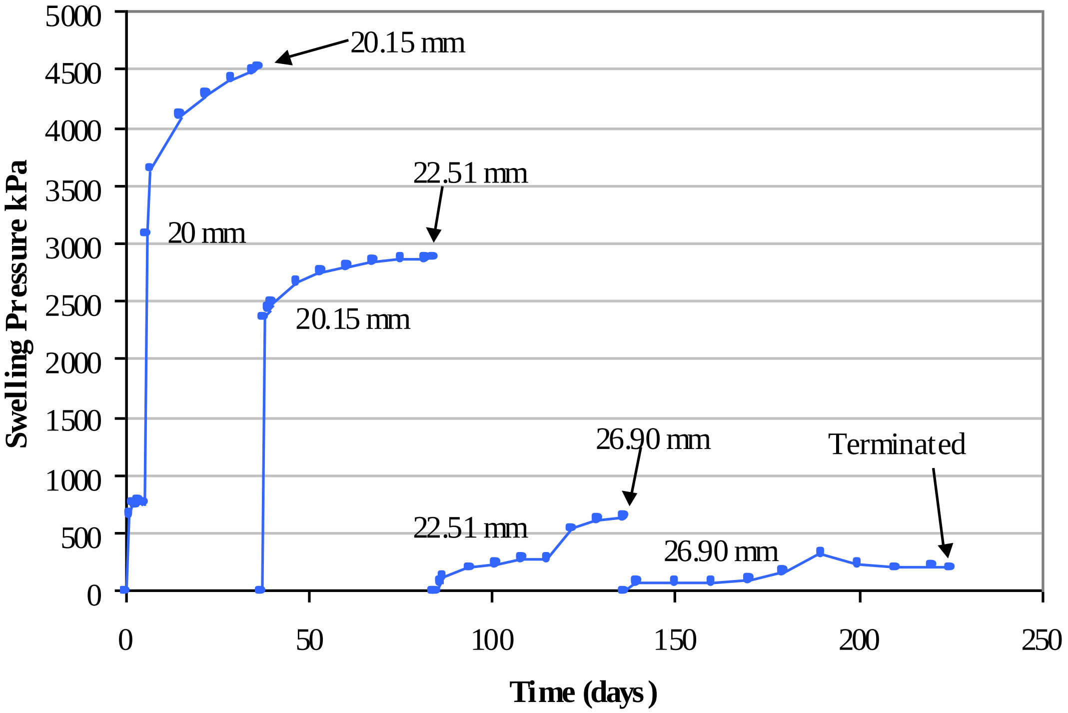

Figure 11: Swelling Pressure as a Function of Time in Experiment 1782 (bentonite dry density 1.60, 1.59, 1.42 and 1.19 g/cm^3) with 100 g NaCl/L Infusion

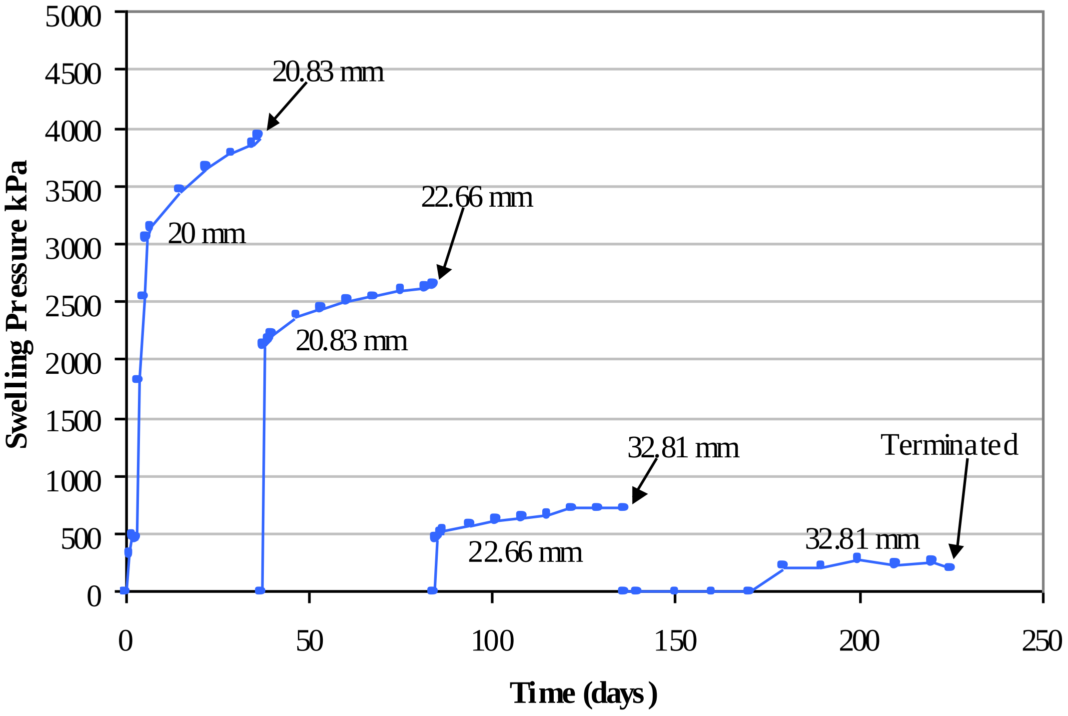

Figure 12: Swelling Pressure as a Function of Time in Experiment 1784 (bentonite dry density 1.60, 1.54, 1.41, 0.98 g/cm^3) with 100 g NaCl/L Infusion

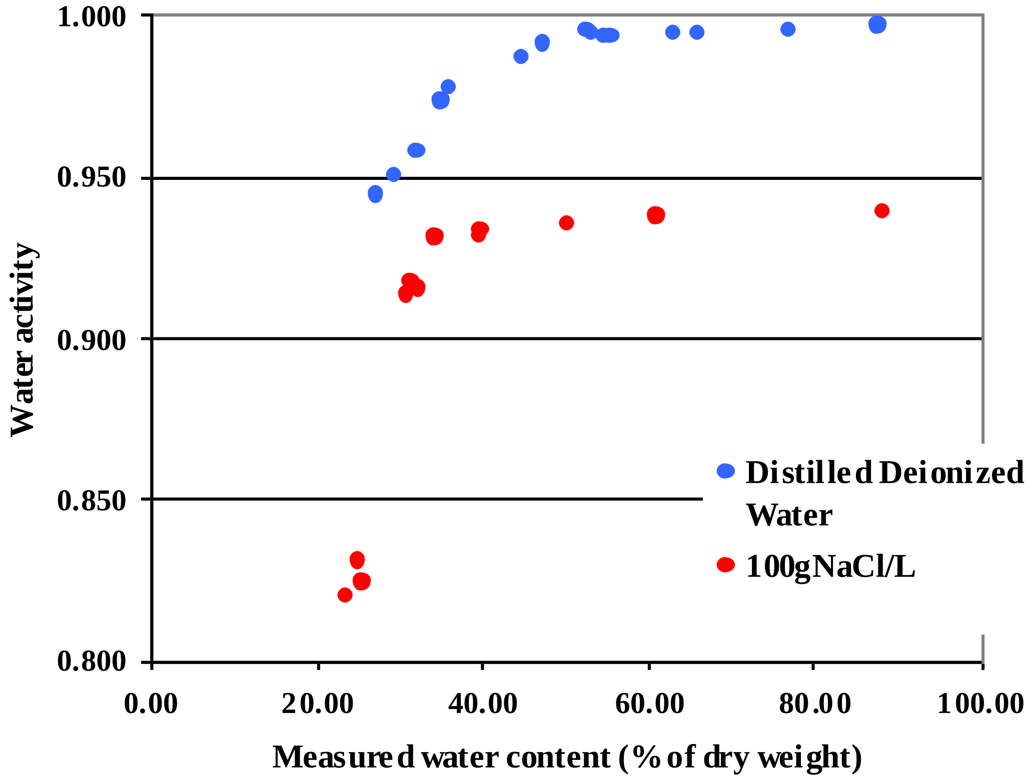

Figure 13: Water Activity as a Function of Water Content (measured in each bentonite plug segment)

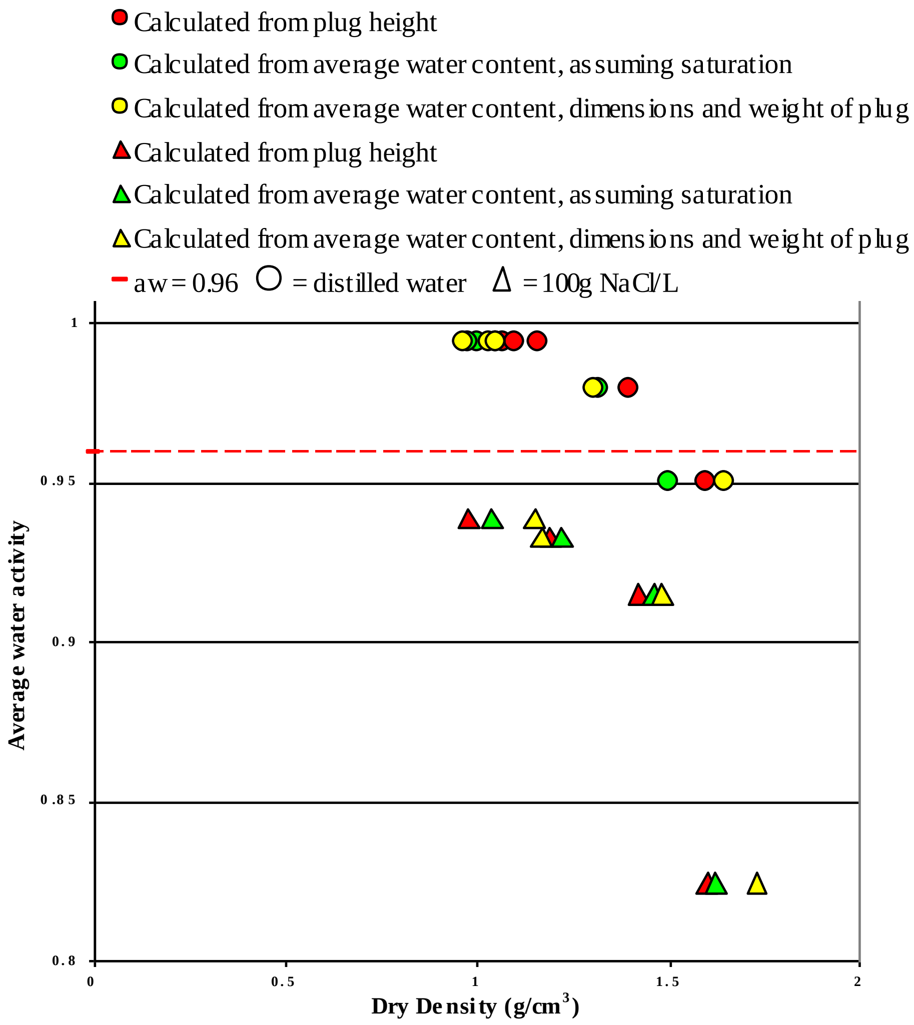

Figure 14: Average Water Activity as a Function of Calculated Dry Density

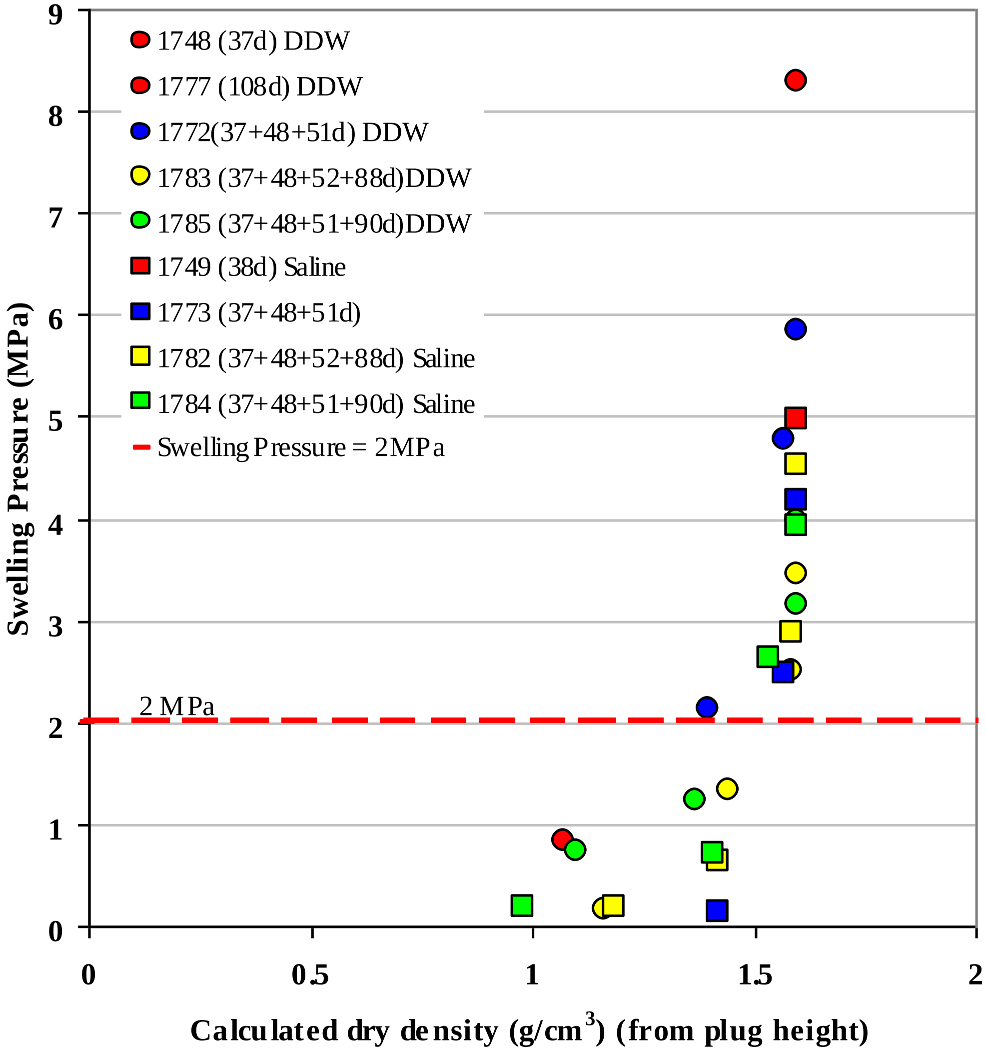

Figure 15: Swelling Pressure as a Function of Dry Density (calculated from plug height)

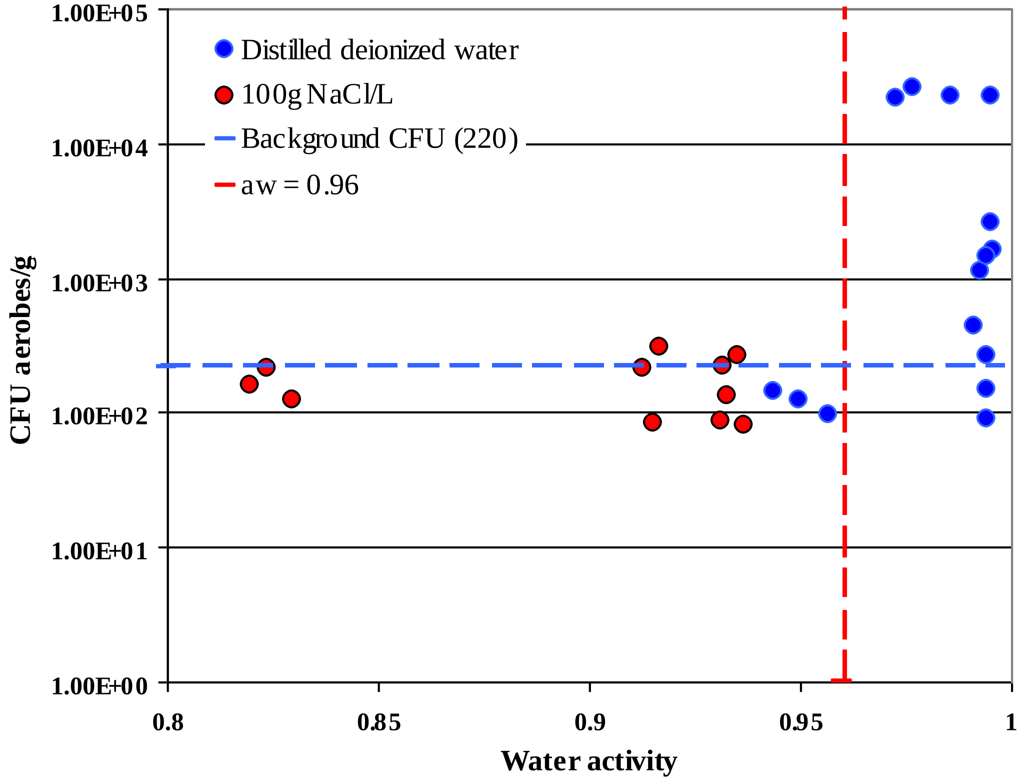

Figure 16: Aerobic Culturability as a Function of Water Activity

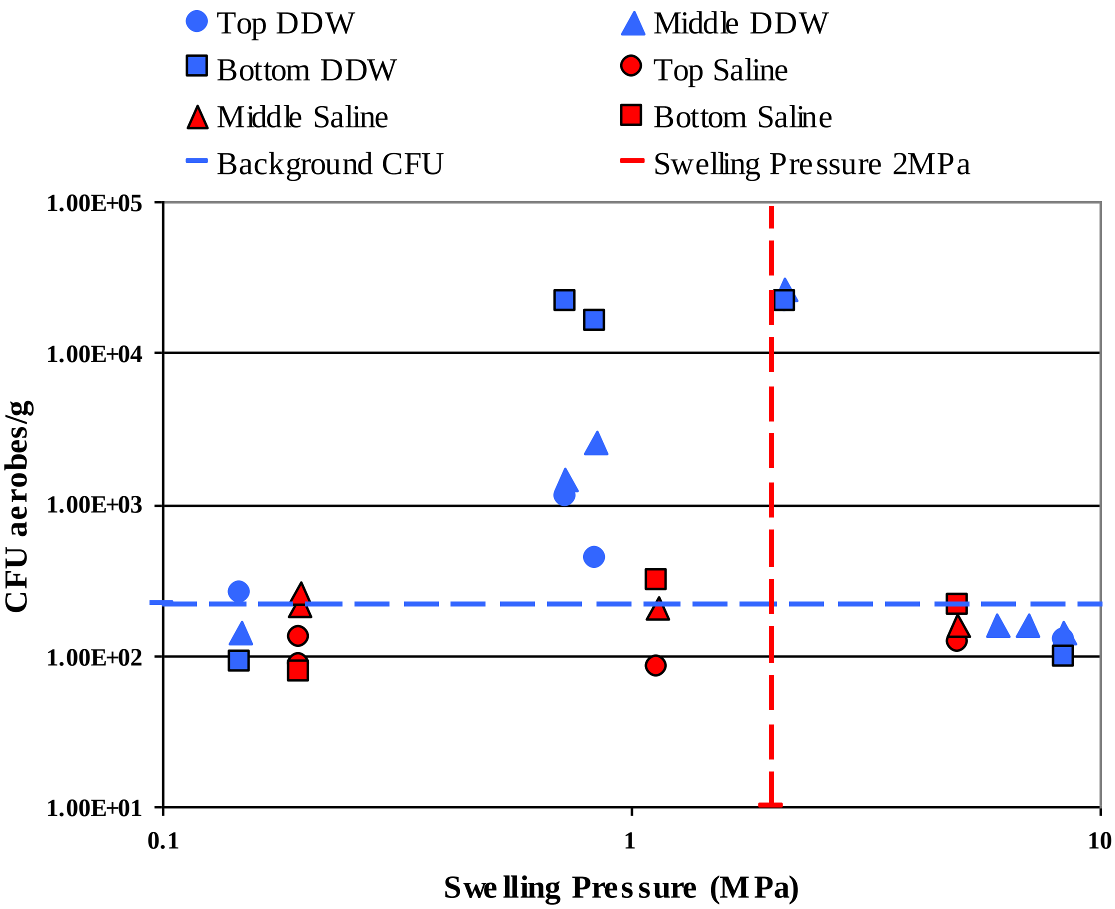

Figure 17: Aerobic Culturability as a Function of Swelling Pressure

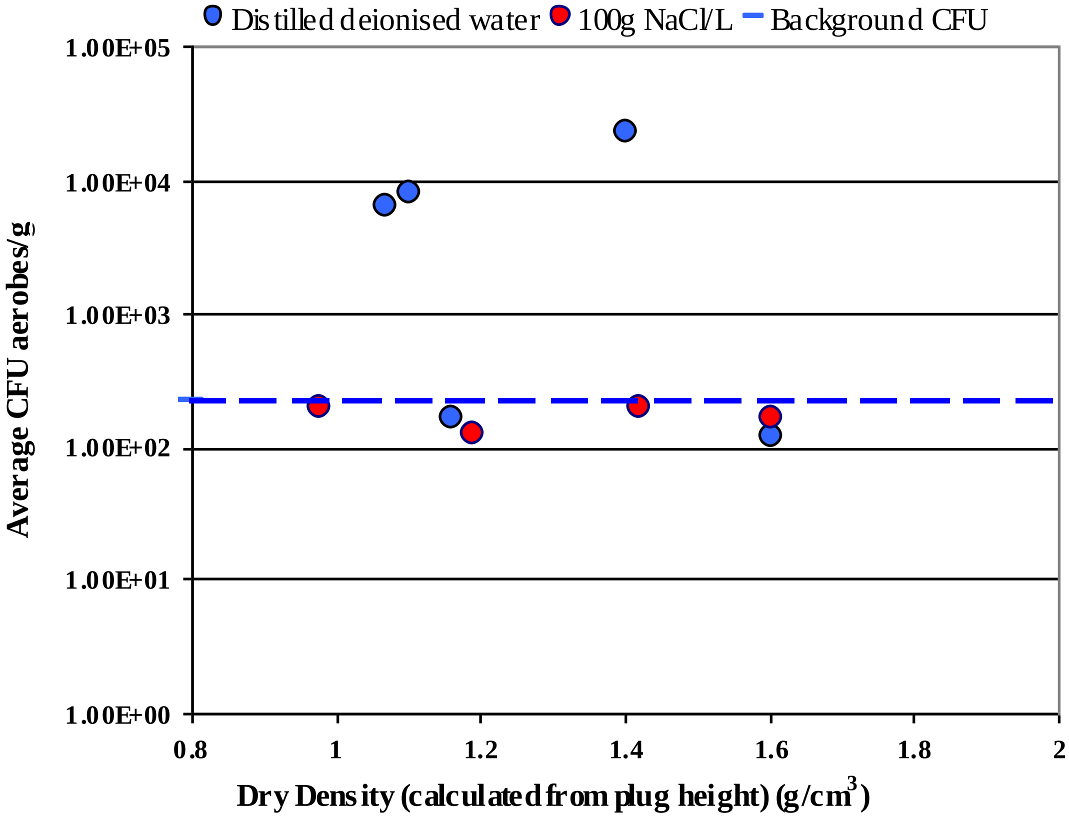

Figure 18: Average Aerobic Culturability as a Function of Dry Density (from plug height)

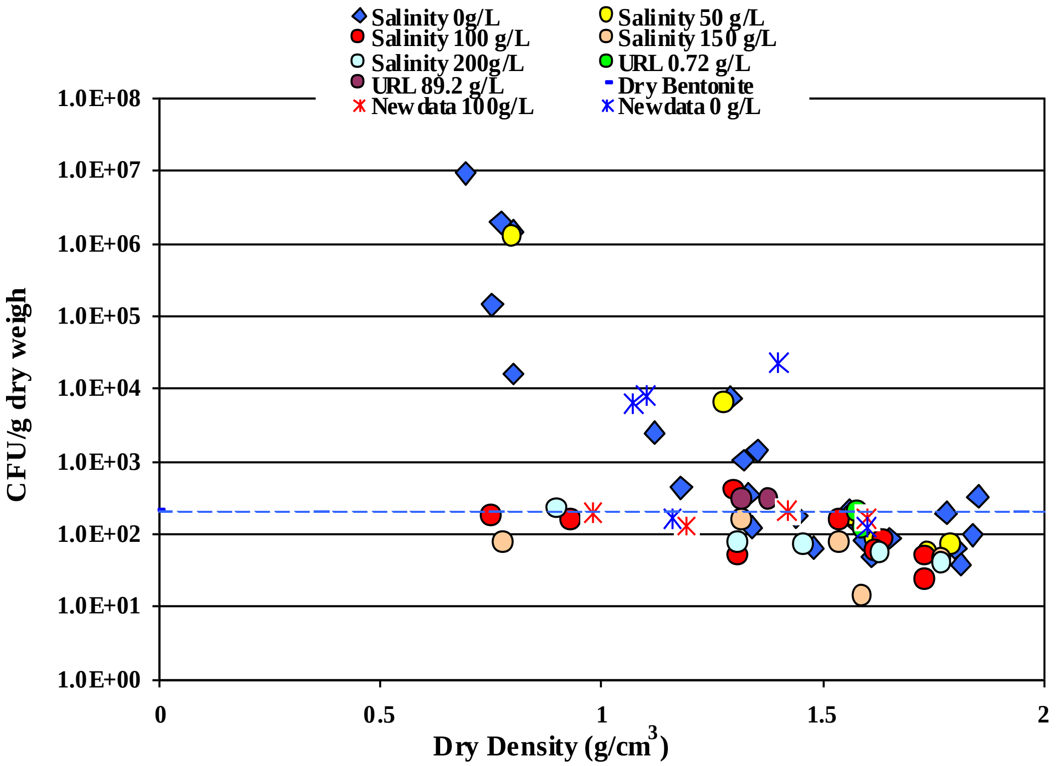

Figure 19: Aerobic Culturability Versus Dry Density, Comparison with Previous Results