CHARACTERIZING AND IMPROVING THE THERMAL CONDUCTIVITY OF ENGINEERED CLAY BARRIERS FOR SEALING A DEEP GEOLOGICAL REPOSITORY

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ABSTRACT

Engineered clay barriers are important components of Canada's concepts for the isolation of used nuclear fuel within a deep geological repository. Different clay-based materials have been proposed for various applications within a repository. These include highly compacted bentonite (HCB), bentonite-sand buffer (BSB), light backfill (LBF), dense backfill (DBF) and gap fill (GF). Characterization of the thermal, hydraulic, mechanical, and chemical (T-H-M-C) properties of these materials is required to evaluate the long-term performance of a repository. The thermal properties of these materials are required to model the dissipation of heat from the used-fuel containers (UFCs). Thermal conductivity is an important repository design parameter since it affects the UFC spacing required to prevent the development of excessive temperatures within the repository. High thermal conductivities are desired since this condition accommodates the rapid transfer of heat from the UFCs to the surrounding rock mass, and in turn allows for a smaller repository footprint.

This paper presents some recent characterization work on the thermal conductivity of the proposed engineered clay barriers. HCB (at low moisture content) and GF pellets were identified as possible insulating layers, having lower thermal conductivity than the desired range of 0.7 W/(m·K) to 0.9 W/(m·K). Preliminary work is presented on increasing thermal conductivity using admixtures such as silica sand, copper powder and titanium dioxide. At low degrees of saturation, silica sand and copper powder increased the thermal conductivity of HCB to the desired range.

1. INTRODUCTION

The Adaptive Phased Management (APM) approach [1] adopted by the Nuclear Waste Management Organization (NWMO) includes several repository geometry options. Figure 1 illustrates two current methods being considered for used-fuel container (UFC) placement in a deep geological repository and the engineered barriers they employ for a crystalline host rock environment. Figure 2 illustrates the horizontal tunnel placement (HTP) method for a low permeability, sedimentary host rock environment.

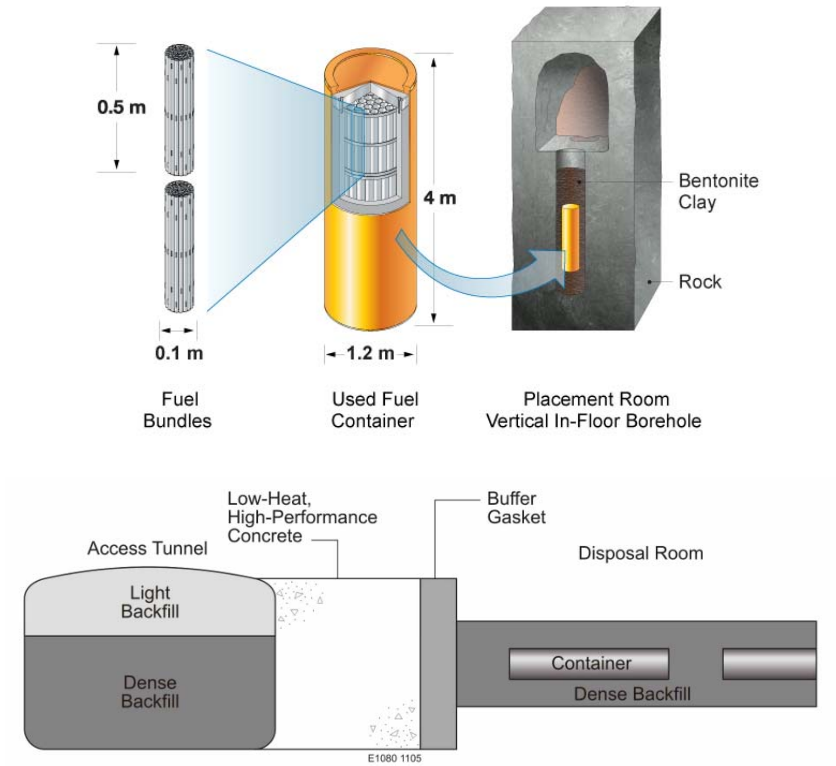

Figure 1. Schematics showing generic UFC placement methods being considered for a used fuel repository in crystalline rock environments. Top: in-floor borehole placement, Bottom: horizontal borehole placement [2]. (Note figures are for illustrative purposes and are not to scale)

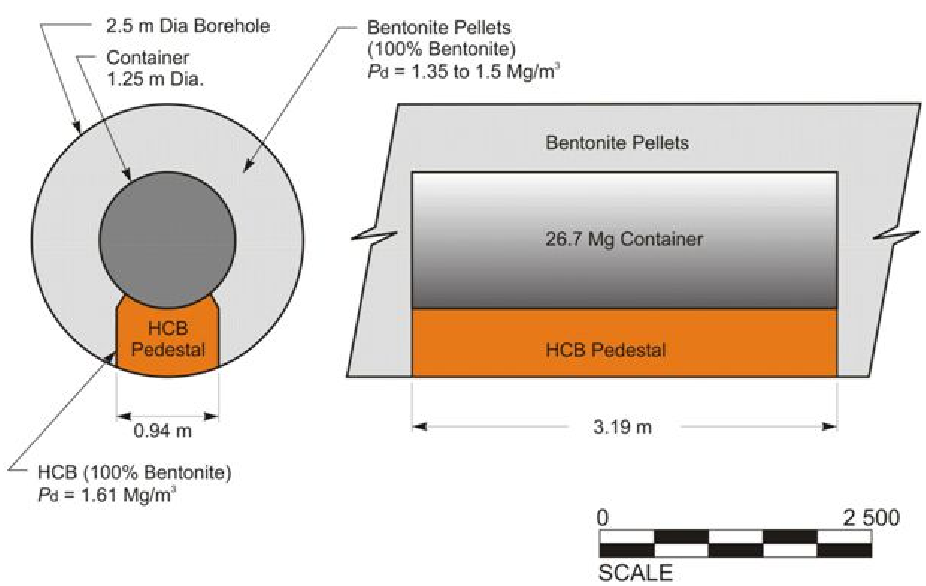

Figure 2. Conceptual arrangement of the HTP Method being considered by the NWMO for sedimentary host rock environments.

Engineered barriers will be required to provide a low hydraulic conductivity (diffusion limited) seal, impart a swelling pressure to support the UFC and excavation, and transfer heat from the UFC to the surrounding rock mass. Different materials are being considered for different functions within a repository as shown in Figures 1 and 2. Options for clay-based materials that have been identified for potential use in a repository have been summarized by [2] and [3]. These materials are described below. Their general properties and target densities are listed in Table 1.

- Bentonite-Sand Buffer (BSB) – a mixture of densely compacted bentonite clay and silica sand, installed either using in-situ compaction or as prefabricated blocks. BSB may be used as a pre-compacted block component beyond the HCB in the in-room placement method or in association with composite plugs or seals.
- Light Backfill (LBF) – a mixture of bentonite clay and silica sand, installed either as loose blended materials or in the form of dense pellets/granules at low-to-medium dry density. Light backfill is proposed for use in filling spaces remaining between pre-compacted blocks used in backfilling and the surrounding rock mass where a high compaction effort will be difficult.
- Highly Compacted Bentonite (HCB) – 100% bentonite clay installed either at high dry density by in-situ compaction or as prefabricated blocks. HCB will be used as buffer immediately surrounding a container in the in-floor borehole or horizontal borehole placement methods and as a supporting pedestal made of blocks in the HTP method.
- Gap Fill (GF) – either bentonite clay, possibly fabricated in the form of dense pellets, silica sand or some combination of the two, which are likely to be installed at low-to-medium dry density to fill the annular gap between the container and the HCB, and between the HCB and the host rock. Pellet fill is a major component of the HTP method.
- Dense Backfill (DBF) – a mixture of glacial lake clay, crushed host rock and bentonite clay, installed either at high dry density by in-situ compaction or as prefabricated blocks. Installation options for this material include compaction into large blocks prior to installation and/or in situ compaction in the access tunnels and shafts of a repository.

While the basic technical premises and requirements of the repository sealing systems have been defined, many of the details related to the specific materials to be used and their properties under repository conditions remain to be evaluated. This is in part due to the evolving technical and performance knowledge related to the sealing system components, and to the broadening of the geologic media under consideration and their particular thermal, hydraulic, mechanical and chemical (THMC) properties. These material properties are required as input to numerical models developed for evaluating the performance of a repository.

Table 1. Summary of general properties and target densities (after [3]).

Property	Bentonite-Sand Buffer (BSB)	Light Backfill (LBF)	Highly Compacted Bentonite (HCB)	Gap Fill (GF)	Dense Backfill (DBF)
Composition	50% bentonite 50% sand	50% bentonite 50% sand	100% bentonite	100% pelletized bentonite	5% bentonite 25% glacial clay 70% crushed rock
EMDD[1] (kg/m^3)	1,150	1,000	1,500	1,250	800
Dry density (kg/m^3)	1,690	1,240	1,610	1,400	2,120
As-placed density (kg/m^3)	1,980	1,400	1,950	1,410	2,280
Saturated density (kg/m^3)	2,060	1,780	2,010	1,880	2,330
As-placed porosity (%)	38	55	41	49	22
As-placed saturation (%)	80	33	65	6	80
Initial gravimetric water content (%)	18.5	15	17	2	8.5
Saturated gravimetric water content (%)	23	46	26	36	10.6

[1] Effective Montmorillonite Dry Density = (mass of bentonite * smectite fraction)/(volume of voids + volume of smectite minerals)

Excessive temperatures must be avoided to prevent damage to the UFC and alteration of the clay mineralogy, which could affect properties such as swelling ability. Therefore, high thermal conductivities are desired to rapidly dissipate the heat to the surrounding rock mass. As a result, thermal conductivity is an important repository design parameter that affects the allowable spacing between UFCs. This spacing, in turn, affects the overall area of the repository and possibly cost. A database of thermal properties of the engineered clay barriers is thus required to model the transfer of heat generated by the UFC to the surrounding rock mass.

This paper presents the work performed in developing a database of thermal properties of engineered barrier materials and begins the process of improving the thermal conductivity of the materials.

2. MATERIALS AND METHODS

2.1 Measurement of thermal conductivity

The device used in the thermal properties testing was a Hot Disk Thermal Constants Analyzer[1]. The system operates by supplying a pulse of constant heat to a sample sensor, which acts as both a heat source for increasing the temperature of the sample and a resistance thermometer to monitor the change in temperature after the heat pulse. The sensor itself consists of an electrical conducting pattern in the shape of a double spiral etched out of a thin sheet of nickel. The conducting pattern is supported on both sides with a thin insulating material consisting of Kapton (Figure 3).

The solution of the thermal conductivity equation is based on the assumption that the sensor is located in an infinite material. This means the total time of the transient recording is limited by the presence of the outside boundaries and the limited size of the sample. An estimation of how far this thermal wave has proceeded in the sample during a recording is defined as the probing depth:

$$\Delta p = 2\sqrt{kt}$$

where Δp is the probing depth (i.e., the shortest distance from sensor edge to specimen edge), k is the thermal diffusivity; and t is the measuring time.

The distance from any point of the sensor to any point on the surface of the specimens must exceed Δp if the total measuring time is t. To determine both the thermal conductivity and thermal diffusivity with good accuracy, the thickness of a flat sample should not be less than the radius of the sensor.

The probing depth only provides an estimate of the required sample size as the thermal diffusivity of the material is unknown, but can be estimated from known properties of materials. In practice the determination is by an iterative process.

As the sensor is heated, the resistance increase as a function of time is given by:

$$R(t) = R_0\{1 + \alpha[\Delta T_i + \Delta T_{avg}(\tau)]\}$$

where R_0 is the resistance of the disk prior to heating and time (t) = 0, α is the temperature coefficient of resistivity (TCR), ΔT_i is the constant temperature difference that develops nearly immediately over the insulation on the sensors, and $\Delta T_{avg}(\tau)$ is the average temperature increase of the sample surface in contact with the sensor.

The temperature increase recorded by the sensors can be represented by:

$$\Delta T_{avg}(\tau) + \Delta T_i = (1/\alpha)\{[R(t)/R_0] - 1\}$$

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[1] Hot Disk Constants Analyzer, TPS2500, manufactured by Hot Disk AB, Chalmers Science Park, Chalmers University of Technology, Sven Hultins gata 9 A, SE-412 88 Gothenberg, Sweden

with ΔT_i becoming a constant after a short time Δt. This can be estimated from:

$$\Delta T_i = \left(\delta^2/\kappa_j\right)$$

where δ is the thickness of the insulating layer, and κ_j is the thermal diffusivity of the layer material.

The time dependent temperature increase is given by:

$$\Delta T_i(\tau) = \left(P_0/\pi^{3/2}ak\right)D(\tau)$$

where P_0 is the power output from the sensor, a is the overall radius of the disk, k is the thermal conductivity of the sample, and $D(\tau)$ is a dimensionless time dependent function. The dimensionless time dependent function is:

$$\tau = \sqrt{t/\Theta}$$

where t is the time measured from the start of measurement, and Θ is the "characteristic time". The characteristic time is defined by:

$$\Theta = a^2/\kappa$$

By plotting the recorded temperature increase versus $D(\tau)$, a straight line is produced, the intercept of which is ΔT_i and the slope is $P_0/(\pi^{3/2}\, ak)$ using testing times longer than Δt_i. Because thermal diffusivity is not known before testing, the final straight line is determined through iteration.

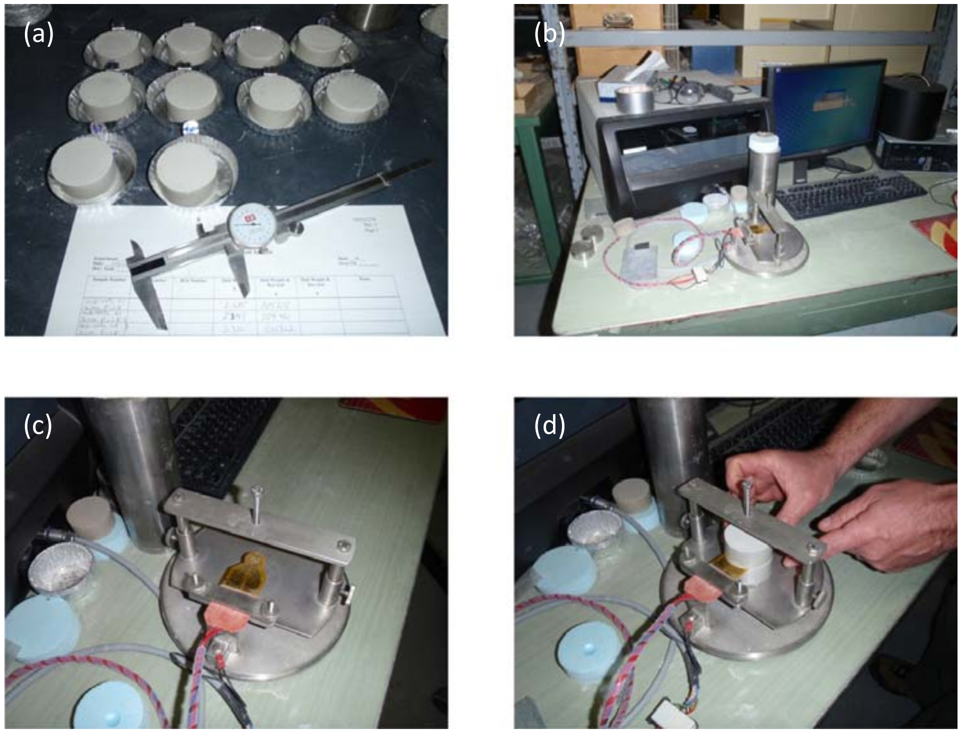

Figure 3. Thermal conductivity testing on pucks of compacted bentonite (a) pre-compacted specimen pucks, (b) sample frame and thermal properties analyzer, (c) sensor installed in specimen frame, (d) specimen pucks installed on either side of sensor in a two-sided test configuration.

2.2 Specimen preparation

The method of specimen preparation depended on the cohesiveness of the material. This in turn determined the configuration of the thermal conductivity measurement test. If the material could be formed into a cohesive, puck-shaped specimen, a standard two-sided test was performed. Two-sided tests (Figure 3) consisted of sandwiching the sensor between two puck-shaped specimens of the material to be tested. The two-sided method was used for BSB, DBF and HCB specimens.

For the puck-shaped specimens, a sufficient amount of material the material to be tested was oven dried for a minimum of 24 hours at 107°C. After the material was removed from the oven and air cooled, distilled water was added by weight using a spray mist bottle with continuous addition and mixing to the desired saturation point. Once mixing was completed the wet material was placed in a sealed container. The material was then allowed to obtain equilibrium between water and sample material for a minimum of 48 hours. The pucks were then produced by compressing a known amount of material with a hydraulic press into a cylindrical steel compression mold (50-mm-diameter, 250-mm-tall). The pucks were then measured dimensionally, weighed, and tested for moisture content (after the thermal conductivity test) to confirm density and degree of saturation. Typically three measurements were made at each saturation value and density with two specimen pucks being prepared for each measurement.

A one-sided test was used when a cohesive puck-shaped specimen could not be produced with the material (Figure 4). A one-sided test is performed by taking measurements with the test material in contact with only one side of the sensor. The material being tested was compacted into a container of known volume. The other side of sensor is in contact with an insulating material with pre-determined thermal properties. In this test series, foam insulating material was used. The one-sided method was used on LBF and GF specimens.

Figure 4. Measuring thermal conductivity of pellet fill using a one-sided test configuration.

Six types of clay pellet-fill materials were tested as possible gap-fill materials (Figure 5). These included four commercially available pellets and two types of pellets developed by AECL. The commercially available bentonite pellets included 3/8" (~9-mm) and 1/2" (~13-mm) cylindrical pellets made of Volclay bentonite, square-shaped pellets made of MX-80 Wyoming bentonite from SKB (16-mm long x 16-mm wide x 8-mm thick), and extruded pellets made of Cebogel bentonite from the BACLO (BAckfilling and CLOsure of a deep repository) project conducted by SKB and Posiva with technical contributions from the NWMO.

AECL used a pellet making machine to produce two additional shapes and sizes of pellets. The machine was a roller-type briquetter that forms pellets by squeezing powdered material between two circular moulds. Each mould has multiple pockets that form one side of the desired pellet size and shape. The moulds are forced together and rotate as powdered material is forced between them from a hopper, via a screw feed. The pressure between the moulds as well as the screw feed rate can be controlled to produce durable pellets. The pellets produced by AECL consisted of narrow oblong shaped pellets (26 mm-long x 10-mm wide x 5-mm thick) and wide oblong shaped pellets (23-mm long x 15-mm wide x 8-mm thick), both of which were made from powdered (200 mesh) Wyoming bentonite (equivalent to the composition of MX-80 bentonite).

1/2" (~1.3 cm) Cylindrical
(Volclay Bentonite)

3/8" (~0.9 cm) Cylindrical
(Volclay Bentonite)

SKB Square
(MX-80 Bentonite)

BACLO Extruded
(Cebogel Bentonite)

AECL Narrow Oblong
(Wyoming Bentonite)

AECL Wide Oblong
(Wyoming Bentonite)

Figure 5. Types of clay pellets (gap fill) evaluated.

3. RESULTS AND DISCUSSION

The thermal conductivity data for a 50:50 mixture of bentonite and silica sand as a function of degree of saturation is provided in Figure 6. This plot applies to both BSB and LBF as several dry densities are presented. The data series labeled as AECL RBM is the Reference Buffer Material developed by AECL in the 1990s. It consists of 50% Saskatchewan bentonite and 50% silica sand by weight. Since, to date, the largest thermal conductivity data set exists for this material, it is used for comparison throughout the current testing program.

Figure 6 indicates similar thermal conductivity values for densities above 1.67 Mg/m^3. Thermal conductivities were, on average, 0.5 W/(m·K) lower for densities of 0.8 Mg/m^3 and 1.0 Mg/m^3. These lower densities are more representative of LBF. As mentioned above, LBF is proposed for use in filling spaces remaining between pre-compacted blocks used in backfilling and the surrounding rock mass. LBF is likely to be placed pneumatically using spraying equipment designed for placing shotcrete materials. Due to this placement technique, which depends heavily on the skill of the equipment operator, the water content can be expected to vary. The density will depend on the material used. Field pneumatic placement trials conducted in Canada [4] and Sweden [5] [6] indicate the achievable dry density will be in the range of 1.0 to 1.2 Mg/m^3 if the material is pure bentonite, and for a 50% bentonite and 50% sand mixture the as-placed dry density will be in the order of 1.2 to 1.4 Mg/m^3. During preparation of LBF specimens for thermal testing, it was found that for degrees of saturation between 40% to 60% it was not possible to achieve the target density (Table 1).

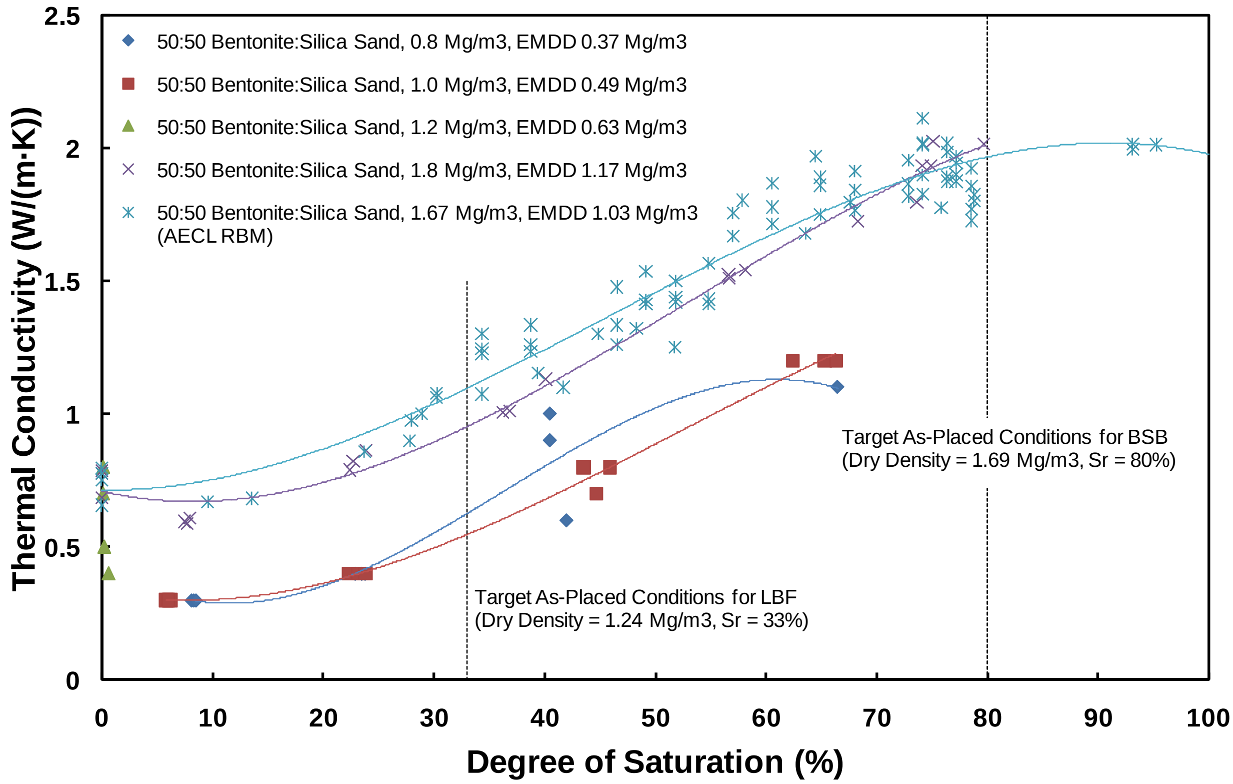

Figure 6. Thermal conductivity as a function of degree of saturation for 50:50 bentonite:silica sand mixtures. (Note Sr = Degree of Saturation)

Figure 7 shows the results for a 40:60 mixture of bentonite and granitic sand. This material was used as the primary clay-based component of a full-scale shaft seal constructed as part of the decommissioning of AECL's Underground Research Laboratory [**7**]. This plot illustrates the effect of different sand sources on thermal conductivity of bentonite sand mixtures. Even for relatively high dry density, the bentonite-granitic sand mixture at a greater sand content than the 50:50 mixture has a lower thermal conductivity than the mixtures made with silica sand. This is attributed to the feldspar fraction in the granite, which has a lower specific gravity and thermal conductivity (~2 W/(m·K)) than quartz (~3 W/(m·K)).

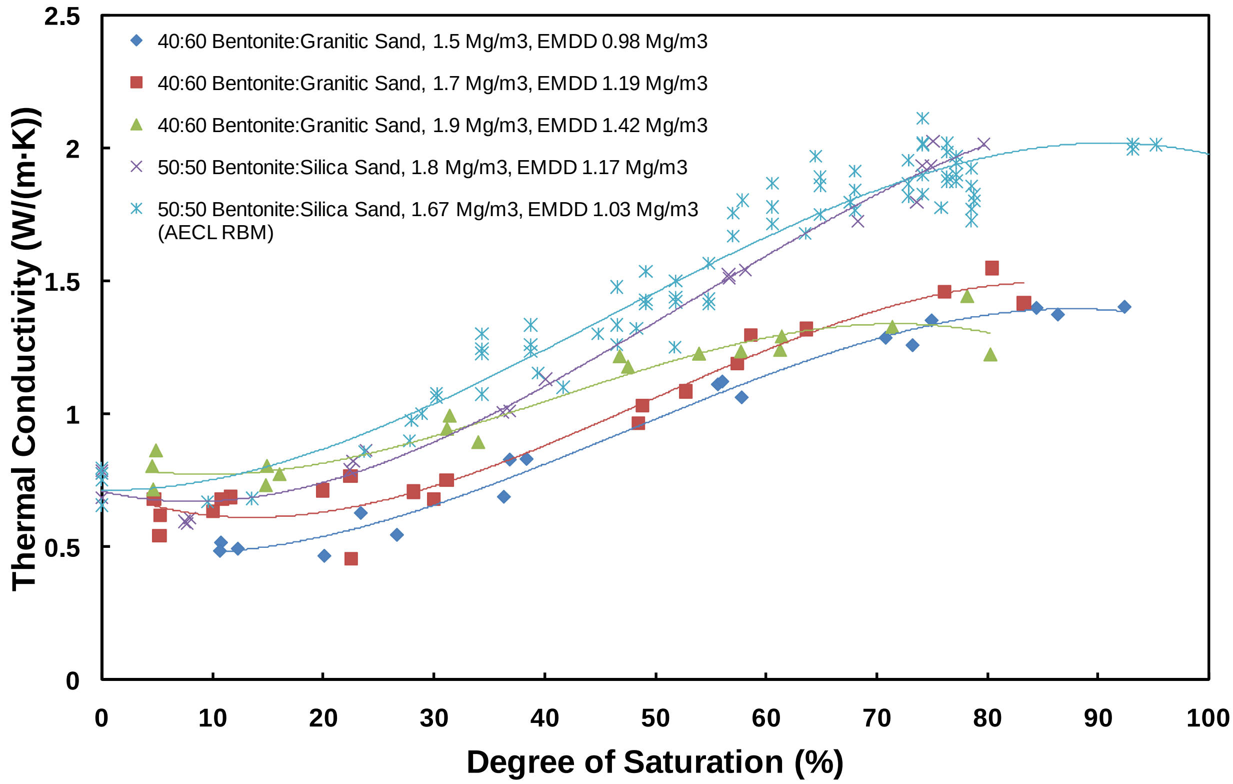

Figure 7. Thermal conductivity as a function of degree of saturation for 40:60 bentonite:granitic sand mixtures.

Figure 8 shows the thermal conductivity data for 100% bentonite as a function of degree of saturation. These data apply to HCB, at a dry density of 1.8 Mg/m^3, and possibly LBF (placed as 100% bentonite with an aggregate size that passes say a 30 mesh), which has a target density of 1.24 Mg/m^3 (Table 1). These data show that thermal conductivity of bentonite increases with density and degree of saturation. As compared to AECL's RBM, the addition of silica sand dramatically increases the thermal conductivity of bentonite by about 0.2 W/(m·K) at lower degrees of saturation to 0.6 W/(m·K) at higher degrees of saturation.

As HCB could be located directly adjacent to the container, an understanding of its thermal behaviour is critical and desiccation of the material is likely. For the target as-placed condition of HCB (i.e., dry density of 1.61 Mg/m^3 at 65% saturation (Table 1)), the resultant thermal conductivity is ~0.88 W/(m·K). At close proximity to a heat-generating UFC, the thermal conductivity can be expected to shift to values of 0.5 W/(m·K) or less due to drying. Any loss of dry density will further reduce the thermal conductivity to as low as 0.2 W/(m·K). This highlights the importance of gap-fill material in maintaining physical continuity (i.e., no air gap), by being thermally conductive itself, and by reducing the loss of density in adjacent sealing materials.

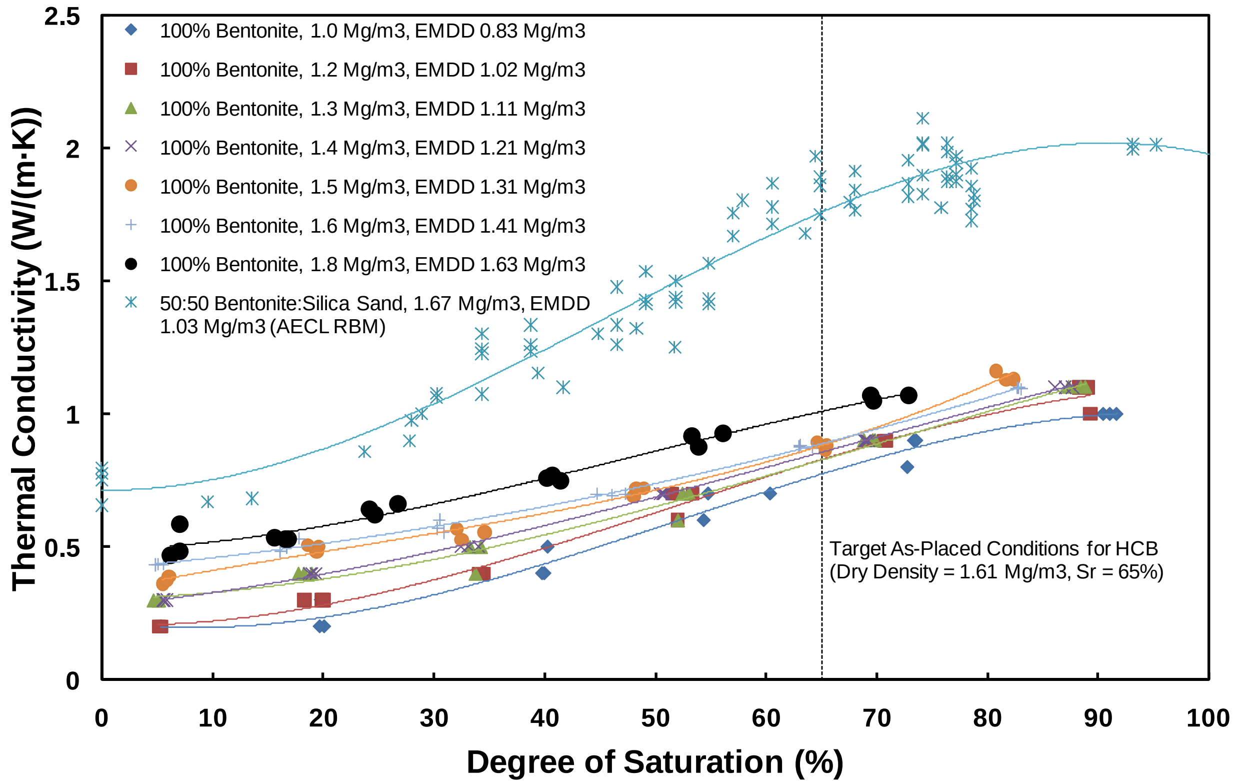

Figure 8. Thermal conductivity as a function of degree of saturation for 100% bentonite.

Although it will not be in close proximity to UFCs, the thermal conductivity of DBF also needs to be known as it will comprise a large portion of some engineered barriers. The results provided in Figure 9 show that DBF has a higher thermal conductivity than BSB at low degrees of saturation. In contrast, at high degrees of saturation the thermal conductivity of DBF is lower than BSB. The reason for this trend is currently unknown and further testing should be conducted. In general, higher thermal conductivities were expected due to the large percentage of crushed rock aggregate. However, the clay fraction may be the limiting factor in the transfer of heat through this material. The higher degree of variability in this data series is due to the larger grain size of the crushed rock aggregate.

Table 2 summarizes the characterization of the four commercially available clay pellets (for use as gap fill or backfill in the HTP method) with the two types of pellets developed by AECL's Geotechnical Laboratory. The data include individual pellet density (dry and bulk), the density (dry and bulk) of a mass of pellets that were poured into a container, the density (dry and bulk) of a mass of pellets after vibratory compaction on a shaker table and the thermal conductivities measured for both density conditions. The results show that the pellets developed by AECL have a higher individual pellet dry density (1.90 Mg/m^3) as compared to the commercially available pellets. The highest dry densities for a mass of pellets were achieved with pellets having a higher length-to-width ratio. These included the extruded BACLO (Cebogel) pellets and the two pellet types developed by AECL. This shape appears to permit the pellets to better align themselves under low compaction efforts. However, the upper values of compacted dry density were close to 1.2 Mg/m^3, which is less than the desired value of 1.4 Mg/m^3 for as-placed pellet fill for use as gap fill or backfill in the HTP method.

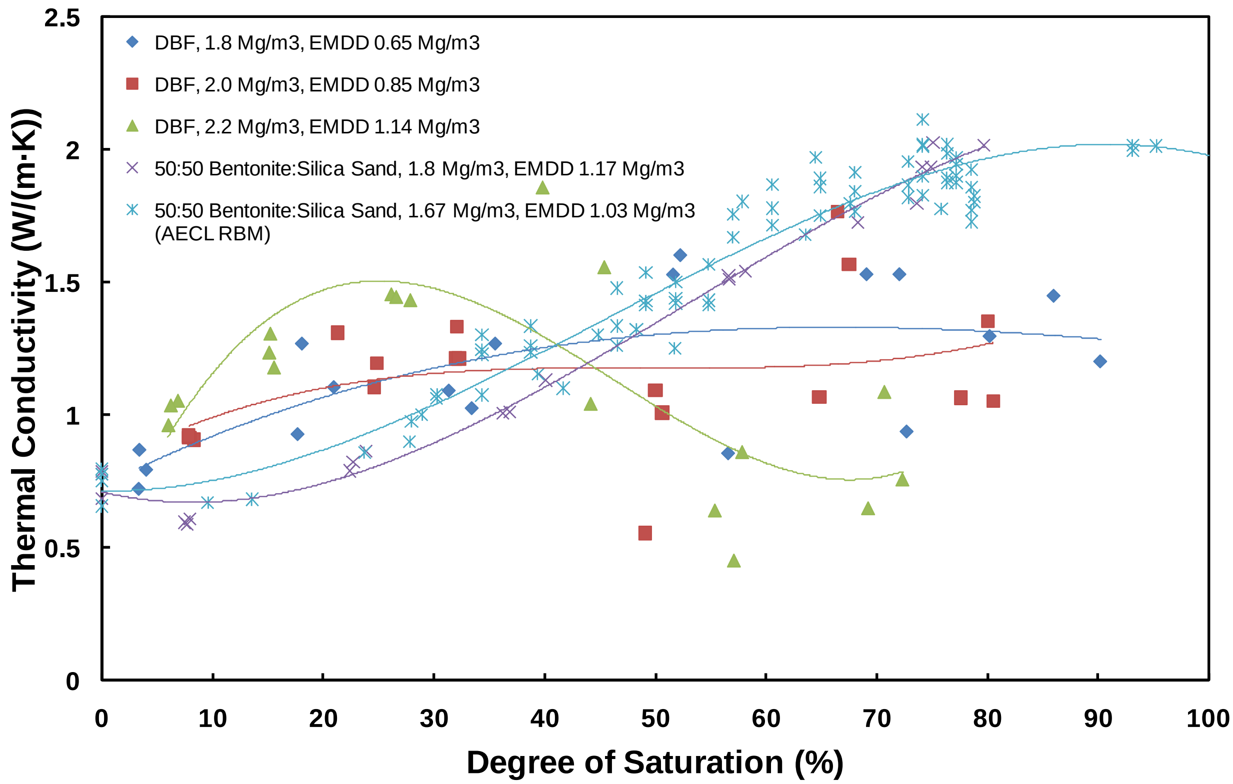

Figure 9. Thermal conductivity as a function of degree of saturation for DBF.

Table 2. Comparison of clay pellets.

	3/8" Volclay Cylinders	½" Volclay Cylinders	SKB Square MX-80	BACLO	AECL Oblong Narrow	AECL Oblong Wide
Bulk Density of Individual Pellets (Mg/m^3)	1.86	1.82	1.92	2.10	2.14	2.11
Dry Density of Individual Pellets (Mg/m^3)	1.72	1.67	1.81	1.83	1.96	1.90
Bulk Density of Poured Pellet Fill (Mg/m^3)	1.05	1.07	1.08	1.13	1.12	1.12
Dry Density of Poured Pellet Fill (Mg/m^3)	0.97	0.98	1.01	1.04	1.03	1.03
Bulk Density of Compacted Pellet Fill (Mg/m^3)	1.18	1.20	1.21	1.30	1.32	1.30
Dry Density of Compacted Pellet Fill (Mg/m^3)	1.09	1.10	1.12	1.19	1.21	1.20
Thermal Conductivity of Poured Pellet Fill (W/(m·K))	0.41	0.40	0.44	0.46	0.45	0.48
Thermal Conductivity of Compacted Pellet Fill (W/(m·K))	0.36	0.49	0.49	0.53	0.51	0.56

Note: compaction effort consisted of 60 seconds on a junior orbit shaker set at 300 rpm.

To evaluate the possibility of further increasing the density of the mass of pellets, a more aggressive technique employing a needle-type concrete vibrator was used in a limited set of trials for the AECL wide oblong pellets. The vibrating technique is more representative of what can be achieved at full-scale and was capable of achieving a dry density of 1.3 Mg/m^3. This is still less than the target dry density of 1.4 Mg/m^3 for as-placed pellet fill (GF in Table 1). Further thermal conductivity testing on pellets, perhaps in combination with a fine grained component to fill the porosity between the pellets, is required. Dixon [8] determined that using a pellet to fines ratio of 80:20, a dry density of 1.4 Mg/m^3 could be achieved at full-scale.

The thermal conductivity data for the various pellet-fill materials are compared in Figure 10. Thermal conductivity of the poured pellet-fill material was still less than 0.5 W/(m·K) for all of the tested pellets. Light compaction increased the thermal conductivity of the pellet-fill material to a maximum of 0.56 W/(m·K) for the wide pill-shaped pellets made by AECL. However, this value is less than the desired range of 0.7 to 0.9 W/(m·K) for gap fill.

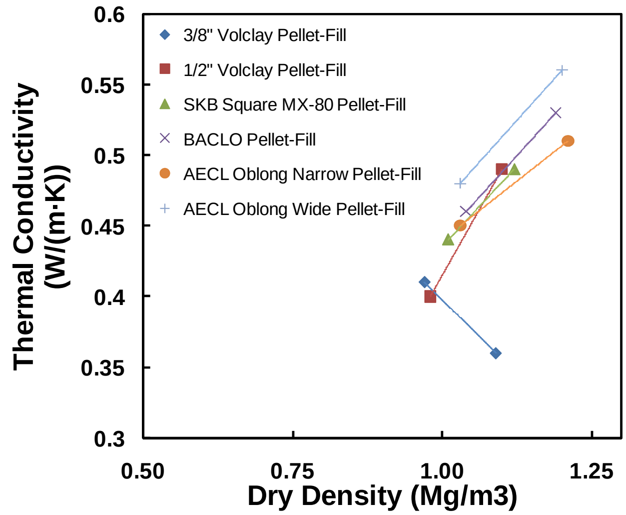

Figure 10. Thermal conductivity as a function of dry density for a variety of pellet fill (gap fill) materials.

The low thermal conductivities measured on materials placed close to UFCs, such as HCB and GF, have implications on the minimum UFC spacing that can be incorporated in repository designs. An illustrative model of the HTP method was constructed for the purpose of estimating the influence of thermal conductivity of the engineered clay barrier on UFC spacing. The results of the modelling exercise are provided in Figure 11. For a maximum surface temperature at a UFC of 125ºC, a thermal conductivity of 0.5 W/(m·K), will require a spacing of approximately 17 m. If the thermal conductivity of the engineered clay barrier can be increased into the range of 0.7 W/(m·K) to 0.9 W/(m·K), the required spacing can be reduced to between 16 m and 14 m, respectively. Although this reduction in spacing may appear small, when factored over the total number of UFCs, a significant reduction in total tunneling length and repository area may be realized. This needs to be compared to the effort and cost of placing gap fill at greater densities in a highly radioactive environment.

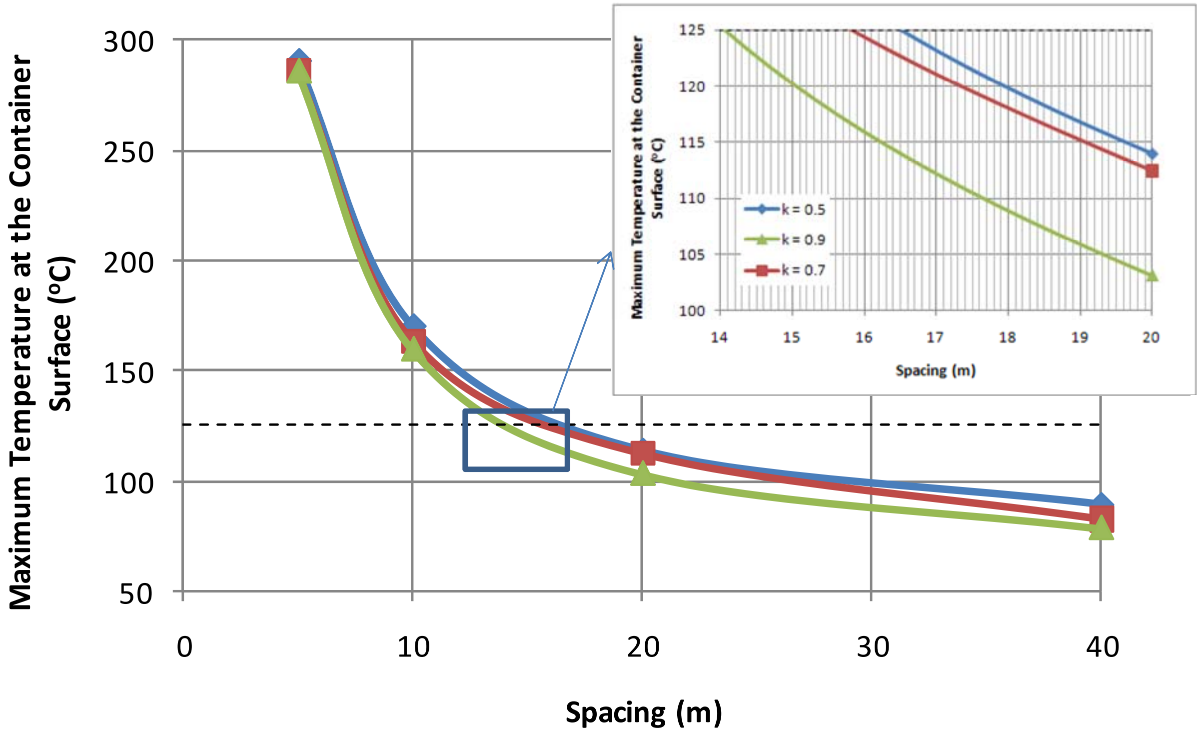

Figure 11. Results of an illustrative model showing the effect of thermal conductivity of the engineered clay barrier in the HTP method on the required tunnel spacing to prevent excessive heat build-up

Based on the low thermal conductivities measured for HCB (at low degrees of saturation) and pellet fill (GF), consideration was given for admixtures to increase the thermal conductivity of these components. Figure 12 compares the thermal conductivity of several bentonite-admixtures to that of 100% bentonite. The results show improved thermal conductivity at low degrees of saturation with the addition of silica sand or copper powder. It is important to note that it is specifically at these low degrees of saturation where the improvement in thermal conductivity is needed. That is, while undergoing the most intense period of heating. At higher degrees of saturation, the effect of increased moisture surpasses the effect of the copper powder, and thermal conductivity values of 100% bentonite are approached. This was not observed for the mixtures containing silica sand. At degrees of saturation in the 65% to 80% range, the addition of silica sand resulted in the thermal conductivity increasing to values close to that of the 50:50 BSB mixture (Figure 6). The relative improvement of silica sand over copper powder for a given mass ratio is due to the higher degree of sand-particle contact.

It should be further noted that the addition of admixtures reduces the mass of bentonite, which in turn reduces the effective montmorillonite dry density (EMDD). EMDD values, provided for each material in the plots, relate to swelling pressure and hydraulic conductivity. Higher EMDDs correlate to higher swelling pressures and lower hydraulic conductivities. As such, consideration must be given to the change in overall performance with the loss of EMDD due to the addition of admixtures designed to increase thermal conductivity.

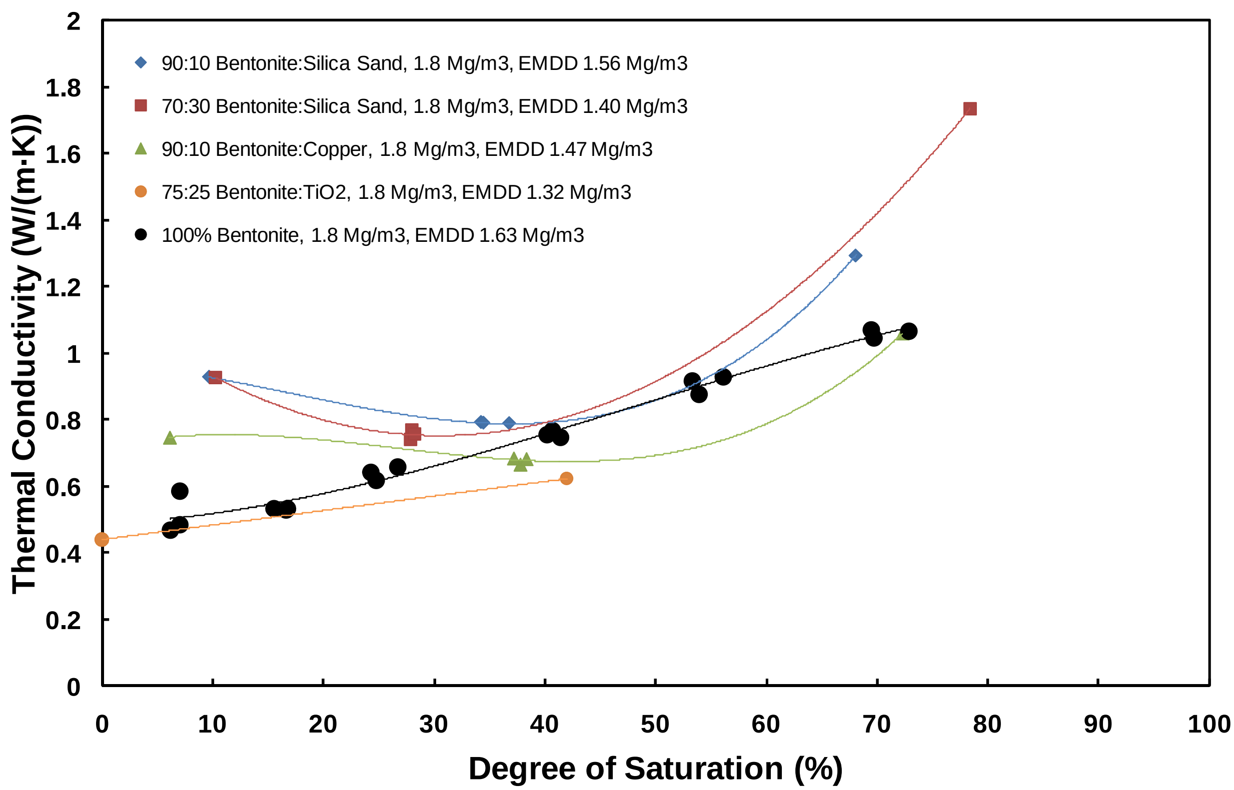

Figure 12. Thermal conductivity as a function of degree of saturation for a variety of bentonite-additive mixtures, compared to 100% bentonite at a constant dry density of 1.8 Mg/m^3.

4. CONCLUSIONS

Samples of LBF, BSB, HCB DBF and GF were prepared at a range of densities and saturations with distilled water and their thermal properties measured. The results indicate lower than desired thermal conductivities for engineered clay barriers that will be in close proximity to heat generating UFCs. Specifically, the thermal conductivity of HCB at low saturations and pellet-fill material is close to 0.5 W/(m·K). This will result in the requirement for larger UFC spacing to prevent excessive temperatures at the surface of a given UFC. Increasing the thermal conductivity of these materials into the range of 0.7 W/(m·K) to 0.9 W/(m·K) will result in a decrease in UFC spacing in the order of up to 2.5 m.

Preliminary work was conducted to examine the effect of adding various admixtures to HCB with the goal of increasing thermal conductivity. The addition of small amounts of silica sand and copper powder resulted in an increase in thermal conductivity to between 0.7 W/(m·K) to 0.9 W/(m·K). This occurred at low degrees of saturation, where the increase is needed most (i.e., during intense heating by UFCs and associated drying).

Further work is being conducted to improve the thermal conductivity of pellet fill (GF). Consideration is being given to other admixtures and the use bimodal mixtures of pellets and fine grained bentonite aggregates to fill the porosity between pellets and therefore increase density and thermal conductivity. Further consideration should also be given to the effect of reduction of

EMDD, and corresponding reduction in swelling pressure and hydraulic conductivity, while attempting to increase thermal conductivity.

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