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GROUND WATER PROTECTION ISSUES WITH GEOTHERMAL HEAT PUMPS

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Abstract

Closed loop vertical boreholes used with geothermal heat pumps are grouted to facilitate heat transfer and prevent ground water contamination. The grout must exhibit suitable thermal conductivity as well as adequate hydraulic sealing characteristics. Permeability and infiltration tests were performed to assess the ability of cementitious grout to control vertical seepage in boreholes. It was determined that a superplasticized cement-sand grout is a more effective borehole sealant than neat cement over a range of likely operational temperatures. The feasibility of using non-destructive methods to verify bonding in heat exchangers is reviewed.

Introduction

Geothermal heat pumps (GHPs) are recognized as being beneficial to atmospheric quality in terms of decreased emissions of CO_2, NO_x and SO_x compared with other means of heating and cooling residential and commercial buildings. Together with relatively low operating costs, the positive environmental attributes have been used successfully to promote the use of GHPs throughout the US. Closed loop vertical boreholes containing the heat exchanger U-loop must be sealed with grout. One concern that has been raised is the potential for ground water contamination if sealing is inadequate.

Research at BNL has investigated means of improving grout thermal conductivity, durability and bond between grout and U-loop (Allan, 1997; Allan and Philippacopoulos, 1998; Allan and Kavanaugh, 1999). The objectives of this paper are to examine the function of grouts in terms of heat transfer and ground water protection, report on the hydraulic properties of cementitious grouts and discuss potential non-destructive tests (NDTs) for verifying bonding and grout quality within ground heat exchangers.

Grout Requirements

The function of the grout is to promote heat transfer between the heat exchanger and surrounding formation and to protect ground water. The first requirement is that the grout maintains suitable thermal conductivity during operation of the GHP. Sufficient heat transfer also demands sound thermal contact at all interfaces. Contact resistance between dissimilar materials needs to be minimized. The creation of gaps at the grout/U-loop and grout/formation interfaces due to either grout shrinkage, thermal contraction of high density polyethylene (HDPE) U-loop, or external conditions leads to an appreciable reduction of the overall conductivity of the system. Decrease in soil moisture content associated with heat rejection and subsequent shrinkage may result in loss of bonding to the grout and consequently reduce the effectiveness of the geothermal heat pump. Another undesirable scenario is inhomogeneity of the grout or incomplete borehole grouting that may arise due to problems with mixing or placement. Therefore, favorable heat transfer in the system requires that the issues of grout thermal conductivity, system component bonding and proper grouting techniques are addressed.

The possibility of interfacial gaps and the impact on GHP performance also need to be considered when modelling heat transfer and calculating required bore lengths. Most models of heat conduction in GHP heat exchangers assume perfect thermal contact between the components (e.g., Gu and O'Neal, 1998). Current work at BNL is examining the impact of contact resistance on heat transfer. Finite element models that can account for imperfect bonding by allowing the presence of gaps at pertinent interfaces are being used.

The specific environmental concerns with closed loop vertical boreholes are cross-contamination of different aquifers and transport of surface contaminants to aquifers. The risk of ground water contamination is primarily controlled by the integrity of the grout sealant. Potential pathways for inter-aquifer communication or contaminants are through the grout itself and at the grout/borehole wall and grout/U-loop interfaces. Thus, the grout should possess low permeability, resistance to shrinkage and cracking, and adequate coupling to the U-loop and surrounding formation under operating thermal loads.

It is clear that physical bonding between system components is important for both heat transfer and ground water protection. Mechanical bonding appears to be of less significance in GHP heat exchangers than physical bonding when considering potential contaminant transport. However, grouted boreholes in seismic zones may be at risk of compromised bond integrity that in turn could pose a threat to ground water quality.

The issues of grout bonding and sealing are not unique to GHPs. Other examples are structural, geotechnical and environmental applications such as grouted tendons and rock anchors, mini-piles for stabilizing soil, sealing of fissures in rock and sealing of nuclear waste repositories. Petroleum, geothermal, water, monitoring and other types of wells also require that the grout or slurry provide sound bonding to the casing and the surrounding formation. Relevant other publications on grout sealants include Lutenegger and DeGroot (1994), Edil et al. (1992) Aller et al. (1989), and Kurt and Johnson (1982).

Grouting Regulations

Regulations governing grouting of vertical boreholes used with GHPs vary from state to state in the US. There are also variations within states. These regulations appear to be modified from existing requirements for water and monitoring wells. Regulatory agencies also specify the piping and any antifreeze used in the loop. The different regulations have been summarized by Den Braven (1998). The National Ground Water Association has prepared guidelines for construction of vertical boreholes (McCray, 1997).

Recently, the New Jersey Department of Environmental Protection approved a superplasticized cement-sand grout developed at BNL for use in consolidated and unconsolidated formations. Neat cement grouts had been permitted in that state in consolidated formations until concerns were raised regarding bonding of this type of grout to the U-loop. The approved cement-sand grout has lower heat of hydration and lower shrinkage than neat cement grouts with similar water/cement ratios. Hence, better bonding and hydraulic sealing are achieved. The grout has higher thermal conductivity than conventional neat cement and bentonite grouts and thereby allows the required bore length to be reduced. This is also beneficial from a groundwater protection aspect. Further details on the grout properties are given in Allan and Philippacopoulos (1998).

Hydraulic Properties of Superplasticized Cement-Sand Grout

A range of different cementitious grout formulations has been tested for coefficient of permeability and bonding to U-loop in order to assess the ability of the grouts to function as an effective borehole sealant. The role of additives such as latex has also been studied. The grouts were tested for coefficient of permeability in the bulk state and when cast around two lengths of HDPE pipe to represent a U-loop. The experimental arrangement and procedure are described in Allan and Philippacopoulos (1998). Tests were performed in a flexible wall triaxial cell permeameter. All specimens were cured in water for 28 days and vacuum saturated prior to testing.

The specimens containing HDPE pipe were tested at different temperatures to elucidate the effect of thermal expansion and contraction on system permeability. Operation of a GHP in heating mode correlates with low fluid temperatures in the U-loop. Since the grout and HDPE have significantly different coefficients of thermal expansion, contraction of the loop could conceivably result in a high permeability pathway at the grout/U-loop interfaces and increase the risk of groundwater contamination. The pipes in the test specimens were sealed with wax so that flow was restricted to either the grout or the grout/pipe interfaces. Specimens were isothermally conditioned in a water bath to the temperature of interest. The permeameter tests did not replicate different temperatures in the legs of the loop associated with flowing heat exchanger fluid. However, ongoing infiltration tests discussed below will examine the effect of different fluid temperatures on hydraulic characteristics of grouted boreholes.

The results presented in this paper are for a superplasticized cement-sand grout that was selected as having the best overall performance in laboratory and field tests while retaining economic competitiveness and simplicity of mixing and handling. The grout was designed for compatibility with the type of paddle mixer commonly used in the GHP industry. The mix proportions are presented in Table 1 and the grout formulation is referred to as Mix 111. Neat cement grouts with different water/cement ratios were tested for comparison and the mix proportions are also given. Findings for other grouts are reported in Allan and Philippacopoulos (1998).

The measured coefficient of permeability for bulk Mix 111 after 28 days of wet curing was $1.58 \times 10^{-10} \pm 5.2 \times 10^{-11}$ cm/s. This is relatively low and meets the required specification of less than 10^{-7} cm/s (Eckhart, 1991). The coefficients of permeability for the grout/pipe specimens at different temperatures are presented graphically in Figure 1. Mix 111 has a consistently lower permeability coefficient than neat cement grouts at all temperatures. The results clearly show that thermal contraction increases system permeability. The test arrangement permitted comparison of different materials under a given set of isothermal conditions. The variation of permeability coefficient with temperature under realistic operational conditions will depend on the thermal distribution throughout the pipe and grout and the resultant thermally induced material deformations. Current finite element analysis at BNL is examining the thermal stresses and deformations in the GHP heat exchanger system and initial results indicate that the gaps caused by contraction will be non-uniform. The gaps will also vary with changes in loop temperature along the length of the heat exchanger. Confining pressure is also expected to influence the system coefficient of permeability.

Table 1. Mix Proportions for Tested Grouts

	Mix 111	**Neat Cement (w/c = 0.4)**	**Neat Cement (w/c = 0.6)**	**Neat Cement (w/c = 0.8)**
Cement (kg/m^3)	590	1369	1087	894
Water (l/m^3)	324.5	547.6	652.2	715.2
Sand (kg/m^3)	1257	0	0	0
Bentonite (kg/m^3)	6.5	0	0	0
Superplasticizer (l/m^3)	8.8	27.4	0	0
Specific Gravity	2.18	1.95	1.74	1.61

Insert Figure 1.

The grout/pipe specimens were subject to wet/dry and thermal cycles. The experimental details are given in Allan and Philippacopoulos (1998). The neat cement grouts underwent cracking and coefficient of permeability could not be measured. In contrast, Mix 111 grout did not fail. The coefficients of permeability for Mix 111 were slightly higher after the cyclic exposure. However, the values remained of the order of 10^{-7} cm/s at 21°C.

Infiltration tests are currently in progress to measure penetration of a head of water above a grouted borehole. The test configuration is similar to that used by Edil et al. (1992) to study the sealing characteristics of different grouts for water wells. The first set of experiments was performed on PVC pipes that contained a single U-loop and were sealed with either neat cement or Mix 111 grout. The tubes were 5.1 m long and 102 mm internal diameter. Each of the tubes contained a 25.4 mm ID U-loop so that interfacial conditions between grout and loop were taken into consideration. Grout was tremied from the bottom up into the tubes using a 25.4 mm diameter tremie tube. A 60 cm long, 102 mm internal diameter PVC tube was glued to the top of the grouted tube. A transparent sight tube was attached to the top tube for viewing water elevation. The top tube was filled with water to give an initial head of 58 cm. The infiltration rate was calculated as the change in elevation with time.

Mix 111 had a consistently lower infiltration rate than neat cement grout. The values after 133 days were 2.9×10^{-7} cm/s and 6.7×10^{-7} cm/s for Mix 111 and neat cement with w/c = 0.6, respectively. No outflow through the total length of the grouted tube was recorded. Infiltration decreased with time due to ongoing cement hydration and associated changes in pore structure. Also, since the grouts were not saturated at the commencement of the tests there may have been some water absorption in the initial stages that contributes to the infiltration rate. Falling head permeability could not be calculated because the length over which flow occurred was unknown.

An arrangement has been constructed to enable infiltration rate to be measured as different temperature fluids circulate in the loop. The specimens are shorter than those used in the above tests in an attempt to reduce the time for outflow to occur and to possibly allow calculation of falling head permeability. The configuration is the same as that in the initial tests except that the grouted length is 80 cm and the initial head of water is 29 cm. The first set of experiments involves testing grouted PVC tubes. The tubes were grouted with either Mix 111 or high solids bentonite grout. The tests are currently being conducted at room temperature until equilibrium is established. The bentonite grouted tubes underwent rapid infiltration of the entire head of water within the first 15 hours. The bentonite itself oozed out of the tube outlet during this period. Therefore, the infiltration tests on bentonite were discontinued. The effect of circulating fluid temperature will be investigated once a steady infiltration rate is achieved in the tubes grouted with Mix 111. It is also planned to thermal cycle the grouted tubes and determine the impact on infiltration rate. The next set of tests will measure the infiltration rates in simulated boreholes in which the grout will be surrounded by soil.

Feasibility of Non-Destructive Testing

Non-destructive tests offer the potential to verify bonding integrity and quality of grouting in-situ. If an appropriate test could be developed to monitor changes in dimensions and bond integrity this would enable better comparison of in-situ performance of different grouting materials. Furthermore, in-situ tests to assure that the borehole is completely grouted would be very valuable both from heat transfer and environmental standpoints. Different non-destructive techniques used in the petroleum industry to verify bonding between well casing, cement and formation have been reviewed for applicability to ground heat exchangers (Allan and Philippacopoulos, 1998). A widely used approach to obtain material information in different wells is through acoustic or sonic logs (Goodwin and Carpenter, 1991). Pulsed Neutron Logging (PNL) has also been used for channel detection (e.g., Sommer et al., 1993). Experience from field measurements has led to the conclusion that there are several advantages and disadvantages associated with both sonic and ultrasonic methods. The omnidirectional character of the transmitter and receiver in sonic measurements is a key disadvantage. First, it requires good tool centralization in order to obtain simultaneous arrivals from all directions. Second, the method is characterized by lack of azimuthal resolution. Therefore, it neglects material and bonding distributions around the pipe. Azimuthal averages usually provide misleading results. By contrast, the major advantage of the ultrasonic technique is that it provides such spatial resolution.

Shear coupling is important for the sonic technique. Lack of shear coupling is caused by the presence of microannuli. Therefore, a second major disadvantage of the sonic techniques is their sensitivity to microannulus effects (Jutten et al., 1993). On the other hand, ultrasonic techniques are not sensitive to shear coupling. They operate by pulses generated to strike the wall surface at normal incidence. When sensitivity to shear coupling, however, is important, then sonic techniques are more efficient than ultrasonic ones. Experimental results from comparisons between the two techniques in a full-scale simulator have lead to the conclusion that combinations of sonic/ultrasonic measurements should be used in field verification programs (Hayman et al., 1995). Additional evidence for using a dual approach (i.e., sonic/ultrasonic) was obtained in an investigation conducted by the EPA (Albert et al., 1988). While several successful measurements were made, the conclusion was that none of the tools used in the study was able to detect channeling in the cement smaller than 30 degrees. Cement channeling of the latter size is considered environmentally unacceptable.

One of the anticipated difficulties for using sonic or ultrasonic methods to evaluate bond integrity in GHP heat exchangers is the size of the tools because the diameter of the HDPE pipe is much smaller than that of injection or production wells and currently available tools will not fit in the typically used pipe. An additional complicating factor arises from the nonsymmetrical configuration of the GHP heat exchangers created by the presence of two pipes. This causes an unequal azimuthal distribution of the grout around each of the pipes. Any arrival times from waves reflected at the grout/formation interface are inherently unequal. In addition, pipe-to-pipe effects may be of importance when resonance is caused in one pipe. Sonic and ultrasonic measurements must be calibrated to take into account the polyethylene pipe vibrations which differ from those of steel pipe as well as the grout dynamic material properties. Engineering calculations, on the basis of the acoustic impedances of representative grouts, must be made to further evaluate the applicability of acoustic methods in determining the in-situ integrity of ground heat exchangers of GHP systems.

Low vibration methods such as those used in non-destructive testing of piles are another possibility. The proposed test procedure is as follows: A vibration transducer is placed at the top of the ground heat exchanger and causes it to vibrate in a specific mode, e.g., vertical motion. The vibration of the ground heat exchanger produces a set of waves that radiate away from it into the surrounding formation. These waves consist primarily of body waves; surface waves as well as interface waves depending on the stratigraphy of the formation. The motion is recorded at the top of the ground heat exchanger. Other locations may also be selected to provide additional response data. The force-displacement relationship for the particular mode of vibration excited during the test is recorded. The latter is conventionally presented in terms of impedance or compliance functions over a dimensionless frequency range which usually represent ratios of wavelengths to some dimension of interest, i.e., radius or height.

Theoretically, the ability of the ground heat exchanger to radiate energy away into the formation depends, among other factors, on the interface conditions between the grout and the formation. The better the bonding the more the radiated energy. This principle can be translated in terms of impedances. Specifically, loss of bonding due to the presence of channeling in the grout would influence the appearance of these curves in specific frequency windows. Therefore, by comparing to a full-bonding curve conclusions can be drawn with respect to the grout/formation interface. Specific ranges can be developed from laboratory testing where specimens can be subjected to vibratory motion. By recording their dynamic response, field specifications can be developed. Furthermore, dynamic analysis of the overall system should be performed using finite element techniques to calibrate these tests. This analysis is part of BNL's current research program.

Conclusions

The presence of gaps at grout/U-loop and grout/formation interfaces in closed loop vertical boreholes is detrimental to both heat transfer and ground water protection. Coefficient of permeability and infiltration tests have shown that the hydraulic sealing characteristics of cementitious grouts can be improved through appropriate mix design. Superplasticized cement-sand grout has significantly better bonding and sealing properties than neat cement grouts due to reduced shrinkage and heat of hydration. Furthermore, neat cement grouts were prone to cracking on wet/dry or thermal cycling which also makes them unsuitable for sealing boreholes. Thermal mismatch between high density polyethylene U-loop and grout causes the permeability coefficient to vary with temperature. Field verification is desirable to ensure that sufficient bonding exists in the grouted borehole. This could be achieved through in-situ permeability and in-situ non-destructive tests. Dynamic analysis of grouted boreholes is currently being undertaken to further explore non-destructive verification of bond and grout integrity.

Acknowledgement

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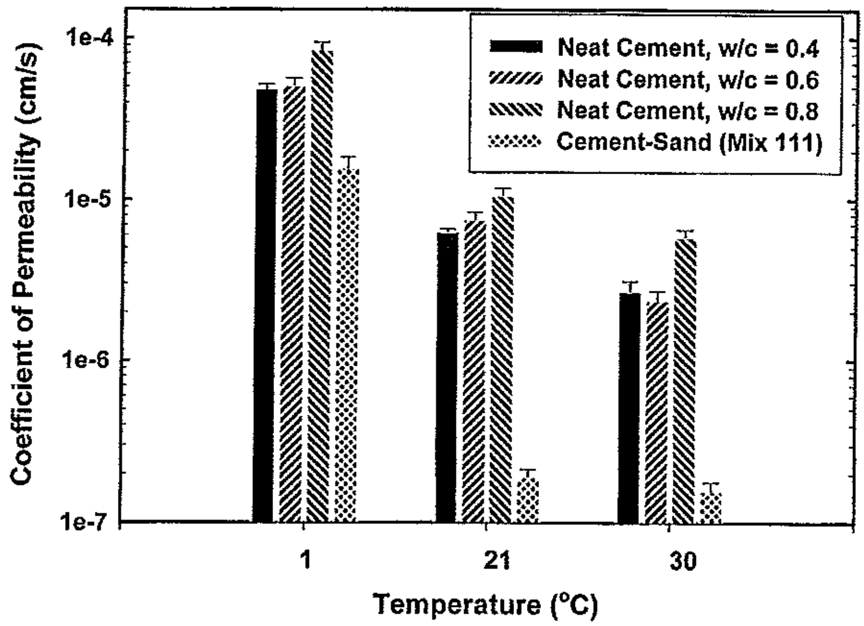

Figure 1. Coefficient of Permeability for Grout/Pipe Specimens at Different Temperatures.

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Informal Report

GUIDELINES FOR MIXING AND PLACING THERMALLY CONDUCTIVE CEMENTITIOUS GROUT (Mix 111)

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1.0 Materials

1.1 Cement

The cement used shall conform to ASTM C 150-Type I. If the site conditions require that sulfate resistant cement is necessary then Type II or Type V cement can be used. Cement that already contains a waterproofing additive should not be used as this has been found to cause slight foaming of the grout and reduce the thermal conductivity.

Cement should be kept dry at all times, stored on pallets and covered with a tarpaulin or plastic sheet. Any bags of cement that are damaged (e.g., torn) or that have been exposed to water should be discarded. The cement should be fresh and free from any hard lumps.

1.2 Bentonite

The decision to use to bentonite will depend on the mixing equipment used. For low shear (e.g., paddle) mixers it is recommended that a small amount of bentonite is used to aid grout stability and reduce segregation of sand. The bentonite used shall be 200-mesh unadulterated sodium montmorillonite. The viscosity of the grout will increase with increasing proportion of bentonite.

1.3 Water

The mixing water shall be potable. Water with excessive impurities may affect the final properties of the grout.

1.4 Silica Sand

The silica sand shall conform to ASTM C 33 in terms of soundness and absence of deleterious substances only. The particle size gradation shall conform to that in Table 1 below. The sand used in this work was purchased from New Jersey Pulverizing Co. (Test Card 3343-97). However, other sand suppliers should be able to blend sand to meet the specified gradation.

The bags of sand should be kept dry at all times and stored on a pallet. Sand that has become wet should not be used as this will increase the water/cement ratio of the grout.

Table 1. Specification for Particle Size Gradation of Silica Sand

Sieve No. (Size, μm)	Percentage Passing (%)
8 (2360)	100
16 (1180)	95-100
30 (595)	55-80
50 (297)	30-55
100 (149)	10-30
200 (75)	0-10

1.5 Superplasticizer

The superplasticizer shall be ~42% sodium naphthalene sulfonate conforming to ASTM C 494 Type F. The product used in this work was Rheobuild 1000 from Master Builders Technologies. Other manufacturers supply equivalent products. Superplasticizer can often be obtained from local concrete ready mixed companies.

2.0 Equipment

The grout can be mixed in either a low shear (paddle) or high shear (colloidal) grout mixer. Mix 111 in the proportions given below has been designed for compatibility with a paddle mixer. Improved sand carrying capacity, decreased water requirement, reduced bleeding and greater flowability of grouts is usually achieved with grouts mixed in colloidal mixers.

It is preferable to use a grout mixer in conjunction with a larger capacity agitator in which the grout is stored and agitated until use. This is necessary to keep the particles in suspension, and, in the case of thixotropic grouts, keep the grout mobile and fluid. As discussed previously, the grout can be pumped continuously from the agitator tank while the next batch is mixed. Thus, pumping is not interrupted and the risk of plugging the tremie tube is reduced. It is critical that a proper grout mixer suited to cement-sand grouts be used. Mixing of the grout by hand, pumps or concrete ready mix trucks is not acceptable.

Piston pumps are recommended for pumping the cement-sand grouts. Excessive wear may be encountered when using a helical rotor (progressing cavity/Moyno) pump. Based on the field trials a minimum 1.25-inch diameter tremie tube with an open end and several side discharge outlets is recommended.

3.0 Grout Mix Proportions

The basic mix is given in Table 2. The amount of grout that can be mixed at once will depend on the capacity of the grout mixer. It is preferable to mix as much as possible per batch.

Depending on the mixing equipment and actual particle size gradation of sand used, the rheology of the grout may vary. Irrespective of the mixer used, it is recommended that trial mixes are performed and water, bentonite and/or superplasticizer adjusted so that suitable pumpability is achieved. However, use of excessive water will be detrimental to the hardened grout properties (e.g., shrinkage, permeability, durability, thermal conductivity) and probably induce segregation of the sand. Superplasticizer should be limited to a maximum of 20 ml/kg cement. This is equivalent to 851 ml (29 fluid ounces) per 94 lb. bag of cement.

Since the grout properties are very sensitive to water/cement ratio and superplasticizer dosage, it is critical that the amounts of water and superplasticizer required for a grout batch are measured accurately. This can be achieved through use of graduated containers or, in the case of water, with a water meter.

Table 2. Mix Proportions and Yield for Batch of Mix 111 Based on One Bag of Cement.

Cement	1 x 94 lb. bag
Water	23.5 litres (6.19 U.S. gallons)
Sand (conforming to spec.)	2 x 100 lb. bags
Superplasticizer	639 ml (21 fl. oz) (approximately, not to exceed 851 ml)
Bentonite (optional)	470 g (1.04 lb)
Yield	72.2 litres (19.1 U.S. gallons)

4.0 Recommended Grout Mixing Procedure

The recommended procedure for mixing the cement-sand grout in a paddle mixer is as follows:

1. Pre-mix bentonite with the required, measured quantity of water until bentonite is uniformly dispersed. (A Jiffy mixer may suffice).
2. Place water-bentonite mix in grout mixer.
3. Place required measured quantity of liquid superplasticizer in mixer.
4. Start mixer at low speed.
5. Mix water-bentonite and superplasticizer for approximately 10 seconds. Care should be to avoid air entrainment by mixing at excessively high speed.

6. Gradually add required quantity of cement in mixer and increase mixer speed. Mix for approximately one to two minutes or until cement is well dispersed.
7. Gradually add required quantity of sand in mixer and increase mixer speed if necessary.
8. Mix grout for specified time (Maximum of 5 minutes should be adequate).
9. Transfer grout to agitator. If agitator is not used then transfer grout to hopper. Grout in hopper should be agitated occasionally with Jiffy mixer or similar.

5.0 Quality Control

Every batch of freshly mixed grout should be measured for specific gravity prior to pumping. This requires use of a mud balance available from companies such as Baroid and the test procedure is given in ASTM D 854-83. The specific gravity is sensitive to water/cement ratio, sand/cement ratio and uniformity of mixing. Mix 111 with the proportions given above has a specific gravity of 2.18 (Density = 18.2 lb./gal). As a guide, the specific gravity should be 2.18 ± 0.02. Measuring flow time in accordance with ASTM C 939 can also be performed to check for grout pumpability and uniformity. All data and any changes in grout mix proportions or mixing procedure should be documented by the grouting contractor.

Samples should also be taken for future laboratory thermal conductivity testing. In this case, the grout should be poured into a suitable leakproof mould, the dimensions of which depend on the equipment that will be used to measure thermal conductivity. The grout samples should be sealed or covered with plastic for 24 hours and maintained at temperature as close as possible to 20-25°C. After 24 hours the samples should be demoulded and immersed in a water bath at 20-25°C to cure for at least 7 days prior to testing.

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DISCLAIMER

Geothermal technologies

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IN THIS ISSUE:

DOE Reorganization Combines Geothermal and Wind Programs

On September 26, a reorganization of the U.S. Department of Energy's (DOE) Office of Power Technologies went into effect. In accordance with that reorganization, the Office of Geothermal Technologies (OGT) was combined with the Wind Program, creating a new DOE office. Peter Goldman, a DOE career employee and former Wind Program director, will lead the office. We welcome Peter as a new member of the geothermal community and wish him well in his new post.

The reorganization includes the reassignments of Lew Pratsch to the Wind Program and Paul Grabowski to the Biopower Program. Lew managed the drilling program for many years, as well as the geothermal heat pump program for which he became widely known as one of the government's leading experts. Paul ably managed the Geothermal Energy Program's long-term research efforts in advanced drilling and enhanced geothermal systems. Lew and Paul were a credit to the Geothermal Energy Program, and we wish them every success as they move on to new career paths.

Lew's and Paul's Geothermal Energy Program duties will be apportioned among those of us who remain with the Geothermal Energy Program: Marshall Reed, Ray LaSala, Ray Fortuna, and I. Given the magnitude of the staffing changes, I anticipate significant changes in the management and administration of the program as well. Laboratory consolidation, a long-standing issue affecting how we conduct business, has been receiving serious consideration. One or more major new initiatives also may be announced in the near future for the revitalization of the program and better recognition of geothermal as an important energy source. In-depth discussions with industry regarding these new thrusts have already begun.

Obviously, the Geothermal Energy Program has entered a period of substantial, if not dramatic, change as we begin Fiscal Year 2000. And with that change comes a degree of uncertainty about the future. But change also represents opportunity, and I see tremendous opportunities for growth in the use of geothermal energy throughout the country. Growth factors, such as market pull supplied by utility restructuring and technology push provided by research and development, will fuel those opportunities. In the not too distant future, some communities could satisfy their total energy needs from geothermal resources. As never before, the ambitious goals stated in our Strategic Plan seem within reach. We should redouble our efforts to make those goals a reality.

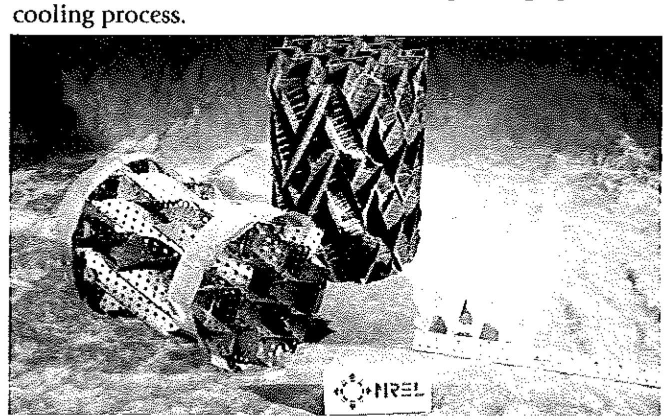
Allan J. Jelacic
Geothermal Energy Program Team

DOE Geothermal Research Wins "R&D 100" Award

Advanced technology for condensing spent steam from geothermal power plants, developed by the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL), earned one of this year's "R&D 100 Awards." *R&D Magazine* gives these prestigious awards to the 100 most commercially promising technical innovations, and it recently honored the developers at a banquet held in the Museum of Science and Industry in Chicago, where the magazine is published.

The award-winning technology, the result of research sponsored by the DOE Geothermal Energy Program, is called Advanced Direct-Contact Condensation (ADCC). It was developed in conjunction with Alstom Energy Systems, Inc. of Easton, Pennsylvania, which has licensed the technology for commercialization. Alstom has already contracted with the national electric utility of Mexico to install an ADCC unit at a new geothermal plant in Mexico.

Conventional steam condensers, known as shell-and-tube condensers, circulate spent steam from electric generating plants around sealed coolant pipes to condense the steam. By contrast, direct-contact condensers mix cooling water directly with the steam in an open chamber, with simple perforated plates inside to provide the surface area on which condensation takes place. NREL's advanced direct-contact condenser design is less expensive than the others, and it increases the efficiency and generating capacity in electric power plants. This increase is accomplished by using sophisticated geometric shapes, called packing structures, to provide the largest surface area for condensation. The ADCC packing structures also channel the steam and water for maximum contact with each other, speeding up the cooling process.



NREL has modeled and tested these packing structures for ADCC technology.

ADCC also offers a major improvement in control of pollution from noncondensable gases in the steam. It does this by a computer program that models the chemical reactions in the spent steam and cooling water, and controls the amount of chemicals needed for emission abatement.

NREL and Pacific Gas and Electric Company (PG&E) demonstrated ADCC technology by refurbishing an existing direct-contact condenser at one of PG&E's geothermal power plants at The Geysers steam field in California. When ADCC went on-line at PG&E's Unit #11, power production efficiency improved by 5%, potential generating capacity dramatically increased by nearly 17%, and chemical cost for emission abatement was cut in half. In an industry where fractions of a percent difference in performance are highly significant, these are outstanding gains. Increased annual revenues at Unit #11 will recover the cost of refurbishment in less than two years.

Market potential for this innovative technology is significant. There are 21 other generating units at The Geysers using direct-contact condensers, as well as many other geothermal power plants worldwide, where retrofit with ADCC could be economically advantageous. With further adaptation, ADCC could also be profitably applied in fossil-fueled power plants, which generally use conventional shell-and-tube condensers. Finally, condensers are common equipment for any industrial process that generates steam or other vapors that subsequently require cooling and condensation. Therefore, ADCC technology could be particularly appropriate for processes such as concentrating fruit juices, for which maintaining low-temperature, low-pressure conditions is important.

When congratulating the NREL winners, Secretary of Energy Bill Richardson said, "These awards are both a tribute to the impressive creativity of the scientists and engineers at our national labs that made these technologies possible, and recognition of the practical contributions that DOE research makes to the country."

ests Reveal Influence

Polycrystalline diamond compact (PDC) bits have yet to be routinely applied to drilling the hard-rock formations characteristic of geothermal reservoirs. Most geothermal production wells are currently drilled with tungsten-carbide-insert roller-cone bits. PDC bits have significantly improved penetration rates and bit life beyond roller-cone bits in the oil and gas industry, where soft to medium-hard rock types are encountered. If PDC bits could be used to double the current penetration rates in hard rock, geothermal well-drilling costs could be reduced by 15% or more.

PDC bits exhibit reasonable life in hard-rock wear tests when using the relatively rigid setups typical of laboratory testing. Unfortunately, field experience indicates otherwise. The prevailing mode of failure encountered by PDC bits returning from hard-rock formations in the field is catastrophic, presumably due to impact loading. These failures usually occur in advance of any appreciable wear that might dictate cutter replacement. Self-induced bit vibration, or "chatter," is one of the mechanisms that may be responsible for impact damage to PDC cutters in hard-rock drilling. Chatter is more severe in hard-rock formations, since they induce significant dynamic loading on the cutter elements.

Chatter happens when the drillstring becomes dynamically unstable and excessive sustained vibrations occur. Unlike forced vibration, the force (i.e., weight on bit) that drives self-induced vibration is coupled with the response it produces. Many of the chatter principles derived in the machine tool industry are applicable to drilling. However, while it is a simple to change a machine tool to study the chatter phenomenon, this is not the case with drilling. Chatter occurs in field drilling due to the flexibility of the drillstring. Therefore, laboratory setups must be made compliant to observe chatter.

Sandia National Laboratories (SNL) modified its Hard-Rock Drilling Facility (HRDF) with the addition of springs, which allow the compliance of field drillstrings for simulation (Figure 1). To represent field-drilling conditions, the range of parameters used in the experimental setup must reflect the conditions typically experienced by a drillstring equipped with a PDC bit. Weight on bit (WOB), rotary speed, and the fundamental vibration modes of the drill-string are important parameters in the experimental design. The penetrating forces and surface speeds for the

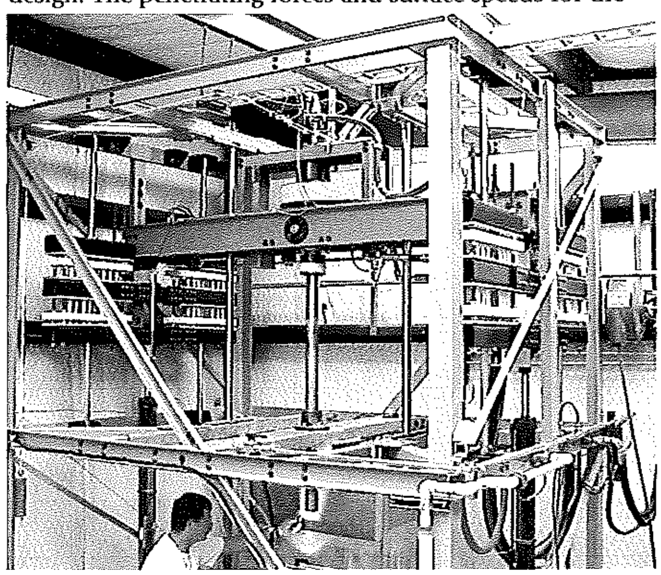


Figure 1. Sandia's Hard-Rock Drilling Facility was modified to include axial compliance.

cutters on the test bit should characterize what cutters experience in the field with comparable formations. The fundamental frequencies of the test fixture were made as low as possible to simulate field drilling. Using this approach, chatter effects observed at the test setup's natural frequency represent the system characteristics at frequencies which may be encountered in the field. Torsional compliance, also inherent in field drillstrings and of particular concern in PDC bit applications, was eliminated in this first phase for simplicity, but it will be addressed in future investigations.

SNL conducted testing in Berea Sandstone, a soft formation, and Sierra White Granite, a hard rock representative of geothermal formations, to determine the conditions under which chatter originates. The tests involved drilling a series of holes at constant WOB and rotary speed while recording drilling parameters for post-test analysis. A displacement transducer monitored the peak-to-peak vibration of the drillstring. Drilling tests were conducted over a range of WOB values and rotary speeds to simulate a variety of conditions.

One measure of chatter severity is the difference between the bit's peak-to-peak vibration and its depth-of-cut per revolution. This parameter, the "out-of-cut distance," is shown in Figure 2 for sandstone. The plot shows the relative amplitude of vibration at various WOB and rotary speed combinations. When the parameter is negative, the bit remains in the cut. Conversely, when the parameter is positive, the bit is bouncing completely out of the cut. The power spectral density has the same general character; it suggests that the out-of-cut parameter is indicative of the vibration energy residing in each of the operating conditions across the measurement range.

The data show that severe chatter occurs in sandstone. This implies that chatter can play a significant role in oil and gas drilling. However, no damage to the PDC cutters was observed throughout the sandstone testing. Like the theory of chatter applied in the machine tool industry, tests

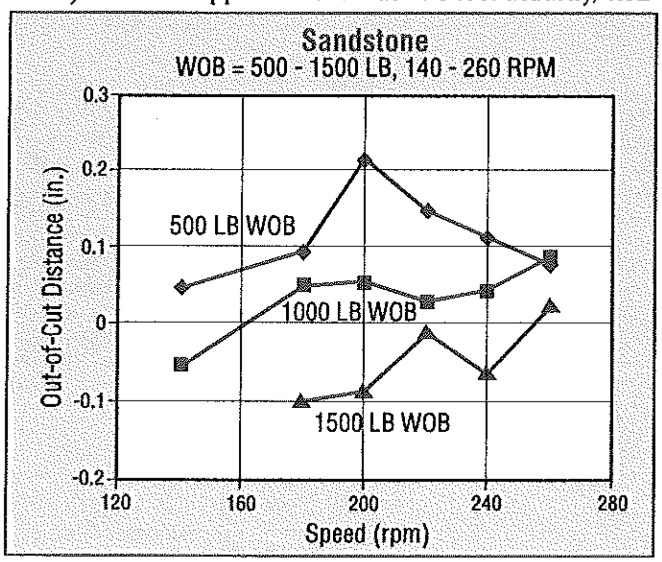


Figure 2. Bit vibration measurements from drilling tests in Berea sandstone.

show that there are pockets of stability (i.e., WOB and RPM pairs) for which the vibration level is reduced. Figure 2 shows that a given WOB has preferential rotary speeds for the drilling configuration represented. Further, although not apparent from the data displayed here, the rate of penetration decreases in the presence of significant chatter. Alternatively, when the chatter level decreases the penetration rate increases. As expected, increasing the WOB at a given rotary speed decreases the chatter. However, even at higher WOB some rotary speeds are better than others. The zigzag nature of the higher WOB data, shown in Figure 2, is due to the excitation of higher-frequency vibration modes at increased WOB.

Important to geothermal drilling, SNL's testing in Sierra White Granite produced chatter with much higher impact loading that led to PDC cutter damage and failure. In fact, the quantity of PDC cutter failures limited the progress of the testing. Figure 3a is a photo of a PDC cutter that drilled 96 feet at 30 feet/hour under stable, non-chatter operating conditions that resulted in the initial stages of wear. Figure 3b shows a cutter that drilled one foot at 10 feet/hour in Sierra White Granite under chatter conditions, resulting in bulk failure of the diamond table and carbide support. These results confirm that chatter is a significant problem when drilling in hard-rock formations. Controlling the level of chatter in the drillstring is crucial when using PDCs for geothermal drilling.

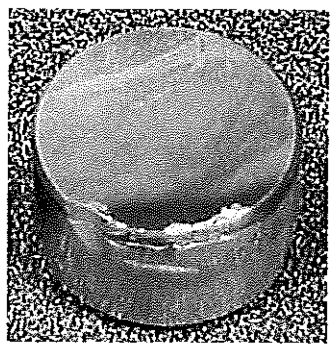


Figure 3a. Lightly-worn PDC at Stable Drilling Condition (96 ft of Sierra White Granite at 30 ft/hr, 2000 lb. WOB and 100 RPM).

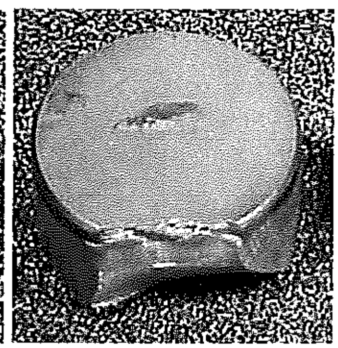


Figure 3b. Failed PDC in Chatter Conditions (1 ft of Sierra White Granite at 10 ft/hr, 1500 lb. WOB and 140 RPM).

SNL is pursuing many ways to reduce chatter. Using a high-speed data link to the bit is one approach. The level of vibration measured at the surface is attenuated from the vibration actually occurring at depth. If accurate dynamic conditions are known downhole, drilling parameters can be modified using feedback control to reduce the chatter level at the bit and improve the drilling process. Another approach is to use a downhole-controllable damper. Such a device would monitor the response of the bit and apply appropriate damping to reduce the chatter level, thereby reducing the impact loading of PDC cutters in hard-rock formations. Yet another approach is to have the HRDF emulate the shock environment that PDC bits must endure under nominal operating conditions. This information will be used to develop advanced cutters that are capable of surviving chatter in the hard-rock formations characteristic of geothermal drilling.

For more information, contact David Raymond, SNL, at (505) 844-8026 or dwraymo@sandia.gov; or Jack Wise, SNL, at (505) 844-6359 or jlwise@sandia.gov. The contributions of Mike Elsayed, University of Southwestern Louisiana, are gratefully acknowledged. SNL is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for DOE under Contract DE-AC04-94AL85000.

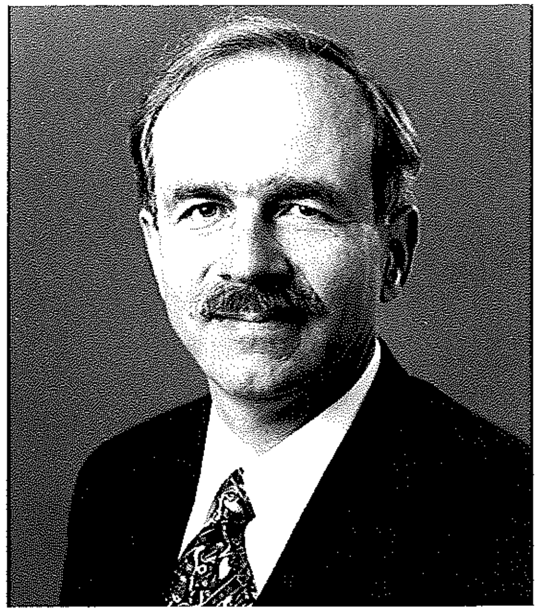
Every research manager dreams of a breakthrough, a major development, a significant contribution to the emergence of an important new technology. The U.S. Department of Energy's (DOE) Geothermal Energy Program had such a manager in Lew Pratsch. His pioneering work that produced the recent growth in the use of geothermal heat pumps (GHPs) fulfills that dream.

Generic heat pump technology is not new, of course; it's basically refrigeration equipment. However, the rapid emergence of energy-efficient, non-polluting GHPs for space heating, cooling, and water heating is, indeed, a phenomenon that is attracting more and more attention. GHPs are increasingly being installed in nearly all types of buildings—from homes, schools, and stores to multistory office complexes. And for the past several years, Lew has been a major player in this process.

But let's back up a bit. Lew is a civil engineer who started his 30-year government career in the field of commuter transportation. First at the U.S. Department of Transportation, and then at DOE, he worked on programs to reduce energy consumption and air pollution by increasing the use of car pools, van pools, and high-occupancy vehicle lanes. And he practices what he preaches: he has driven a commuter van pool between Washington, D.C., and the Virginia suburbs for more than 22 years.

Lew joined the Geothermal Energy Program in 1984 as a program manager for the construction of the experimental 50-megawatt Heber Binary Power Plant in California's Imperial Valley. Soon he was given additional responsibility for the geothermal direct use program, and in this role he became fascinated with the possibilities of GHPs (now called GeoExchange). He was particularly intrigued with the load-leveling benefits that the technology provides to electric utilities. He realized that GeoExchange is a three-way winner: consumers save money on their energy bills, utilities improve their load factors, and the country reduces air pollutants. So, he became an advocate.

To start, Lew brought the fledgling GHP industry together with large, established, influential organizations such as the Edison Electric Institute, the Electric Power Research Institute, the National Rural Electric Cooperative Association, and the U.S. Environmental Protection Agency. He helped educate those organizations' leaders about the exceptional benefits of GHPs, and out of these groups, the Geothermal Heat Pump Consortium was born. The industry has recognized his large contribution to this effort with several awards. And once again, he practices what he preaches: his second home uses GeoExchange. He only paid a dollar a day to heat and cool its 2300 square feet when it was rented.



Lew Pratsch was manager of DOE's geothermal drilling and heat pump programs.

This was not the end of Lew's contributions to the Geothermal Energy Program. After the Heber plant was completed, he was asked to head up the department's research and development (R&D) program in geothermal drilling. Sandia National Laboratories (SNL) in New Mexico performed much of the technical work in this program, and Lew was instrumental in coordinating SNL's research with the geothermal industry's needs. Through the Industrial Review Panel of the Geothermal Drilling Organization, the Geothermal Resources Council, and the Geothermal Energy Program's annual Program Reviews, he helped shape the R&D agenda to meet industry's highest priority requirements.

He also emphasized the importance of developing drilling technologies for application in the oil and gas industry, since the geothermal drilling market alone often lacks the critical mass required to commercialize innovations. For example, acoustic telemetry technology, as a result of last year's licensing agreement between SNL and Baker Hughes, will be applied first in the oil and gas industry. Then, as the market develops and costs decrease, the technology will be applied in the geothermal industry.

For Lew, there's more to life than work. He, his wife, and two sons are all avid water-skiers, and they love to spend their summer weekends in their ski boat on Lake Anna in

Virginia. His son, Craig, a high school sophomore, is having a great year of achievements: straight A's in school last year, an Eagle Scout award in the spring, and barefoot water skiing last summer.

Under the reorganization of DOE's Office of Power Technologies, Lew is now leaving the Geothermal Energy Program and transferring to the Wind Program. But he's made his mark in geothermal energy and will be remembered for it.

erformance

Boreholes used with geothermal heat pumps (GHPs) require grouting. In the past, minimal attention was given to the selection of grouting material for GHPs. The same bentonite grouts used by the water well industry were also used for GHP applications. Bentonite is a relatively poor thermal conductor, and it is also prone to severe cracking and shrinkage under drying conditions. Interest in GHPs has rapidly expanded in recent years, and this has coincided with efforts to decrease installation costs and improve efficiency.

One way of achieving these goals is to increase the thermal conductivity of grout used to complete boreholes. Dr. Marita Allan and Dr. A.J. Philippacopoulos at Brookhaven National Laboratory (BNL) are conducting research on thermally conductive cementitious grouts for use with GHPs. BNL's research covers experimental characterization of a wide range of grout properties, numerical modeling of grout behavior under thermal loads, field demonstrations, and technology transfer to industry.

INCREASING GROUT CONDUCTIVITY

Thermal conductivities up to three times higher than bentonite and neat cement grouts were achieved through appropriate selection of grout ingredients and mix design. The new BNL grout is called Mix 111. Mix 111 basically consists of cement, water, silica sand, and small amounts of superplasticizer and bentonite. It is simple to mix, cost-competitive, and retains thermally conductive properties in the dry state, whereas conventional grouts undergo dramatic decline in conductivity. By increasing the thermal conductivity, it is possible to reduce the required bore length and thus save on installation costs.

The University of Alabama performed analysis showing that the bore length can theoretically be reduced by up to 22%-35% for a particular test case—depending on various other factors such as soil conductivity and bore diameter—by using the cement-sand grout rather than conventional grouts. Cost calculations predict economic viability of the grout compared with bentonite-sand mixtures. While control of initial costs is important, long-term performance of the grout is essential. Mix 111 has been designed to provide better thermal coupling throughout the service life of a GHP, which decreases the life cycle cost.

SUCCESSFUL FIELD TESTS

Oklahoma State University and Sandia National Laboratories conducted field tests in two different climates and geologies. They confirmed the enhanced performance of BNL's Mix 111. Figures 1 and 2 display the initial results, showing that thermal resistance decreased by 29% and 35% when compared with bentonite grout for the two sites, respectively. Further testing is in progress.

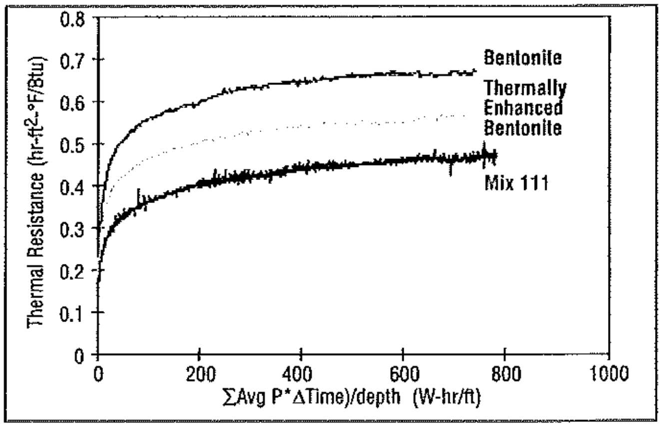


Figure 1. Results of field tests conducted by Oklahoma State University indicating 29% reduction in thermal resistance with Mix 111 compared to bentonite.

WORKING WITH INDUSTRY AND REGULATORS

Besides thermal conductivity, Mix 111 has several other advantages that ultimately resolved some environmental regulatory concerns in New Jersey. The New Jersey Heat Pump Council contacted BNL in search of an alternative to neat cement grout, since permission to use this material had been denied by the New Jersey Department of Environmental Protection (NJDEP). The situation arose due to questionable bond integrity between neat cement

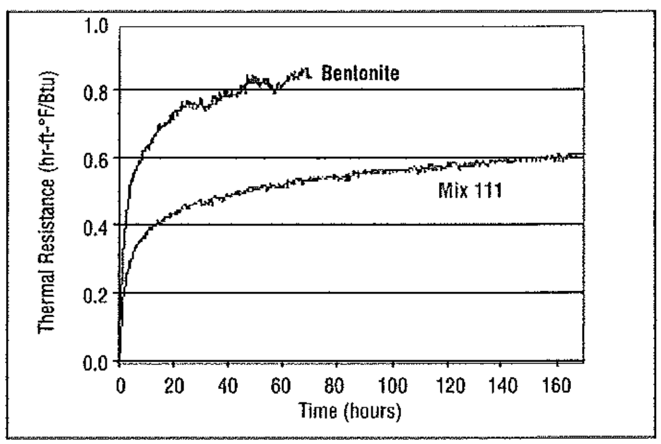


Figure 2. Results of field tests conducted by Sandia National Laboratories indicating 35% reduction in thermal resistance after 70 hours with Mix 111 compared to bentonite.

grout and U-loop, and the possibility of aquifer contamination if channeling occurred at the interfaces. As a result of the injunction, installation of GHPs in consolidated formations in that state halted, and the loss of business was estimated at $3 million in less than one year.

The superior performance of Mix 111—including its reduced coefficient of permeability, lower infiltration rate, shrinkage resistance, and better bond strength to U-loop—convinced the NJDEP that the environmental risk would be minimized by using it rather than neat cement. Finite element analysis of thermal stresses developed in the grouted borehole was used to alleviate concerns of cracking induced by expansion of the U-loop (see Figure 3). Mix 111 was approved for use in both consolidated and unconsolidated formations in November 1998. The New Jersey state permit conditions now include specifications for mixing and pumping Mix 111.

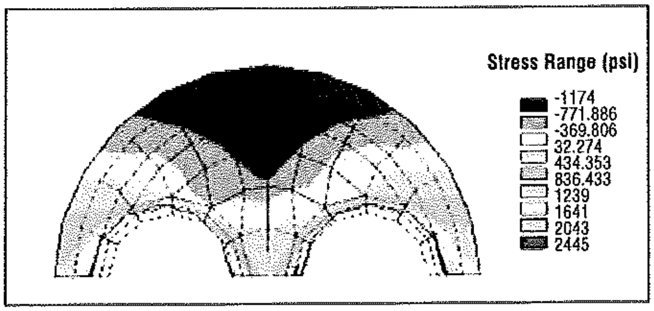


Figure 3. Finite element analysis of thermal stresses in grouted borehole operating in cooling mode. (BNL data)

COMMERCIAL USE

To date, Geothermal Services, Inc., has used Mix 111 on five residential projects in New Jersey, and a test bore was grouted for a future Hilton Hotel project (Figure 4). Based on experience in New Jersey, it has been calculated that bore length reductions of 15% are required for breaking even on Mix 111 material costs, as compared with bentonite grout. This can be achieved given the significantly higher thermal conductivity of Mix 111. Several other commercial projects in New Jersey and other states are pending.

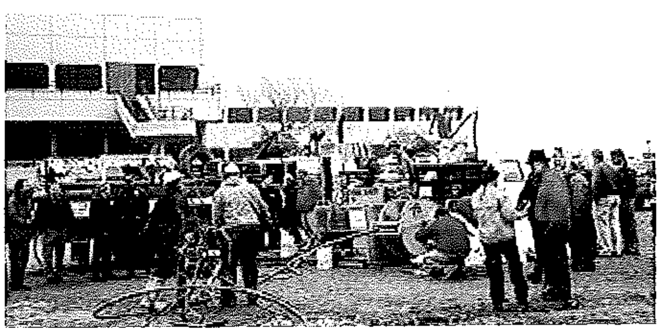


Figure 4. The training session and field demonstration of BNL grout at future Hilton Hotel site in Dover, New Jersey, was conducted in collaboration with NJHPC, Geothermal Resource Group, Geothermal Services, and GPU Energy. (BNL photo)

Enlink Geoenergy Services and Ted Wynne Engineering also used Mix 111 in prepackaged form on the Gallatin Middle School project in Tennessee, which involved 130 boreholes at 300 feet deep. Project engineers were extremely satisfied with Mix 111's high thermal conductivity, consistency from hole to hole of the grout conductivity, independence of performance from the depth of water table, and aquifer protection. Marked improvement in reproducible heat transfer, compared with backfilling the boreholes with soil cuttings, resulted from appropriate grouting techniques and materials. The additional cost of using Mix 111 was nominal and worth the benefits of long-term efficiency and functionality. The grout material costs were only about 2.7% of the overall project costs.

For further information, please contact Dr. Marita Allan at BNL at (516)344-3060.

The U.S. Department of Energy's (DOE) Idaho Operations Office, on behalf of DOE's Geothermal Energy Program, has awarded three cost-sharing grants under the Geothermal Direct Use Drilling Program Solicitation for Financial Assistance.

DOE awarded a $260,000 grant to the Modoc Joint Unified School District in Alturas, California, for drilling an injection well. The direct use project will provide space heating for two schools, Alturas Elementary School and Modoc Middle School, with an enrollment of more than 700 students. Energy savings from the project should allow the school district to realize as much as $73,000 in energy cost savings per year, thereby freeing up funds for enhanced educational programs. Substituting geothermal energy for fuel oil also will eliminate air pollution from hydrocarbon combustion.

Another grant was given to the I'SOT, Inc. geothermal district heating project in Canby, California, for drilling a production well. The developer will retrofit existing propane heating systems to accept heat from a hot water loop. Twenty-nine buildings will be heated and supplied with domestic hot water. In addition to replacing fossil fuels, the developer is planning to create wetlands with the geothermal effluent, which could serve as a habitat for birds on the Pacific flyway. DOE's cost share is $144,000, or 75% of the drilling cost. The California Energy Commission is supporting non-drilling aspects of the project.

Finally, Alex Masson, Inc. received a $296,000 grant for drilling a production well to expand a commercial greenhouse near Radium Springs, New Mexico. The proposed well, which will target the deep parent reservoir of the Radium Springs geothermal system, is expected to provide heat equivalent to 14,000 barrels of fuel oil, or 85 million cubic feet of natural gas, per year. The new well should double the amount of acreage under cultivation.

Since 1962, the International Association of Business Communicators (IABC) has been honoring the outstanding work of communications professionals. In IABC's 1998-1999 competition, the National Renewable Energy Laboratory (NREL) received the "Award of Merit" for a series of four fact sheets it completed for the U.S. Department of Energy's (DOE) Geothermal Energy Program's Geothermal Heat Pump Program.

The titles of these fact sheets are:

- *Environmental and Energy Benefits of Geothermal Heat Pumps*
- *Geothermal Heat Pumps Score High Marks in Schools*
- *Geothermal Heat Pumps Make Sense for Homeowners*
- *Geothermal Heat Pumps for Medium and Large Buildings.*

They provide an engaging and encouraging overview of geothermal heat pumps as a proven technology well on the way to substantial market penetration and success.

A quote from the judging committee sums things up nicely:

> "An admirable job, given the difficult challenges and limitations characteristic of working in the public sector. The series is thorough and the writing clear. A good example of 'effectiveness on a tight budget.'"

Lew Pratsch, the DOE program manager in charge of the Geothermal Heat Pump Program, supervised the series. Bruce Green and Kara Stewart, both with NREL, performed the research, writing, and development of this award-winning fact sheet series. A fifth fact sheet entitled *Geothermal Heat Pumps for Federal Buildings* has just been printed.

IABC presented NREL with the above 1999 Bronze Quill Award.

urbo-Drill Ready to Field Test

The U.S. Department of Energy's (DOE) Geothermal Energy Program will collaborate with DOE's Office of Fossil Energy (OFE) on a field test of an advanced drilling system, which is applicable to both geothermal and some natural gas wells.

The Geothermal Energy Program, which was then the Office of Geothermal Technologies, originally provided funding to Maurer Engineering for the development of the Turbo-Drill—a down-hole, mud-driven drilling motor. After further refinement, the motor was coupled with a gear reducer to provide better torque. OFE then helped review the initial proposal at its Federal Energy Technology Center in Morgantown, West Virginia.

Maurer is now ready to field test and commercialize the technology, and OFE and the Geothermal Energy Program will cost-share this phase of the project. This latest successful agreement results from the National Advanced Drilling and Excavation Technologies (NADET) Memorandum of Understanding between these offices. Past combined efforts through NADET have included proposal review assistance; the co-funding of research and development for advanced drilling systems; technical advice on strategic planning; and the regular exchange of programmatic information.

The new coupled system is a significant advance in down-hole drilling motor technology. It promises to greatly reduce the costs of drilling the extremely hard rock associated with geothermal and natural gas wells.

For more information, contact Allan Jelacic, DOE, at (202)586-5340.

oward Commercialization

The May 1999 issue of *Geothermal Technologies* reported that Sandia National Laboratories' (SNL) innovative rolling float meter (RFM) was being used to help drill a relief well targeted at a burning gas well near Bakersfield, California. Epoch Wellsite Services, Inc., the mud-logging company for both wells, requested the RFM because of the excellent control it provides for accurate drilling, especially when mated with Epoch's RIGWATCH drilling instrumentation system. It's now time to report that the relief well successfully intercepted the gas well; the fire is out, and the blowout is capped.

This dramatic field success for SNL's new technology resulted in a request to install another RFM on a Berkeley Petroleum, Inc. well about 20 miles north of Bakersfield. SNL technicians have completed its installation and calibration. The data from the well will be used to evaluate the circulation monitoring system software program, currently under development by Marconi, Inc., for real-time detection of kicks and lost circulation.

Because of these successes, three more companies—Epoch Well Information Services, International Logging Overseas, and Petron—are pursuing the acquisition of RFMs. Industrial procurement of the device will mark the first commercial deployment of this technology.

SNL developed the RFM through the Lost Circulation Technology Program of the U.S. Department of Energy's (DOE) Office of Geothermal Technologies, which is now the Geothermal Energy Program.

For more information, contact Allan Jelacic, DOE, at (202) 586-5340; or SNL's George Staller at (505) 844-9328 or Gary Whitlow at (505) 844-5755. SNL is a multiprogram lab operated by Sandia Corporation, a Lockheed Martin company, for DOE.

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echnology Innovation

The U.S. Department of Energy's (DOE) Geothermal Energy Program recently announced four awards for advanced research in geothermal technology innovation. The awards, which will total about $300,000, were made under a solicitation for proposals issued by DOE's Golden Field Office.

The DOE solicitation sought proposals to identify, examine, and evaluate innovative ideas that have significant potential to reduce the cost of geothermal energy development or increase the availability of economic geothermal resources. All awards require a minimum private partner cost share of 20%.

The awards (see Table 1 below) cover only Phase I of each project: establishing scientific or technical feasibility of the innovative approach or concept. At the conclusion of Phase I, which will last up to 12 months, the Geothermal Energy Program will review final reports and evaluate proposals for Phase II follow-on work, which may last up to 24 months. Total DOE funding is expected to be $1 million, subject to the availability of appropriations, for those projects selected for Phase II.

For more information, contact Jeff Hahn at the DOE Golden Field Office in Golden, Colorado, at (303) 275-4775

Table 1. Phase I Awardees.

Organization	Project Title	Objective
FAS Engineering, Inc.	Improved Energy Conversion for Geothermal Power Plant	Build and test a two-phase reaction turbine
Michigan Technological University	Highly Impact Resistant and Thermally Stable Rock Drill Bits —A Nanometer Diamond Composite and Near-Net Shaped Manufacturing Technology	Develop and advanced drill bit technology for reducing geothermal drilling costs
Technology International, Inc.	Fracture Resistant TSP Diamond Cutters for Drag Bits	Increase the fracture toughness of TSP diamond to improve the penetration and durability of drag bits
Two-Phase Engineering and Research	Brine Enhanced Air-Cooling	Design, fabricate, and test a small-scale system that will use geothermal brine to evaporatively cool the air as it enters the air-cooled condensers

Outside the Loop

A Newsletter for Geothermal Heat Pump Designers and Installers

Spring 1999 - Volume 2, Number 2 - Published Quarterly

Developments in Ground Conductivity Testing

Several requests have been received from readers to address the issue of in-situ thermal conductivity testing of potential GCHP sites. The tests involve drilling a test bore, insertion of a typical vertical ground heat exchanger, loading of the loop with a constant heat source, and the determination of conductivity from the change in loop temperature.

Developments during the last two years have significantly improved the capability of predicting ground thermal properties and ground loop design accuracy. An additional benefit of these tests is that drilling conditions determined during the installation of the heat exchanger can be provided to loop contractors. This information is critical to providing an informed bid price for installing the ground loop. **Ground conductivity testing helps minimize two of the most common barriers to affordable loops; overdesign and high contractor pricing to cover unknowns in the ground.**

There are debates regarding details that will fine-tune the test procedures when they are resolved. Although ASHRAE has approved a project to evaluate and enhance the procedures, it will be at least 18 months before the project is complete. The good news is that instead of debating if a certain formation has a conductivity of 1.0 or 1.4 Btu/hr-ft-°F, testers are now discussing if the value is 1.21 or 1.29 Btu/hr-ft-°F. Additional good news is that a ±10% uncertainty in formation conductivity will typically result in less than a ±5% uncertainty in loop length requirement which will impact equipment capacity by less than 1% if high efficiency heat pumps are specified. (Details of this calculation will appear in the next issue of *Outside the Loop.*)

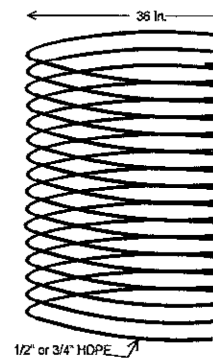
One issue is the length of time the test should be run. Proponents of 12-hour (or less) tests, that are based on the line heat source solution, claim they can screen data to arrive at accurate values even when there are minor heat input variations. Other methods suggest longer tests are necessary. The focus of debate is the impact of the near bore properties. The figure on the following page shows temperature profiles from the center of a test bore out into a typical formation.

The profile for a "12-Hour" test is compared with a "48-Hour" profile in a soil with a 1.5 Btu/hr-ft-°F conductivity, a 250 ft. x 5 in. bore, and a 4.5 kW source. The bore grout conductivity for the 12-Hour test is 0.4 Btu/hr-ft-°F while the grout for the 48-Hour test is 1.4 Btu/hr-ft-°F. Note the large temperature gradient in the bore (66.5 to 90°F) for the 12-Hour test

Continued on Page 2

Large Diameter Bore Coils

An alternate to conventional U-tube designs for vertical ground coupled loops has recently emerged in California. Coiled piping (reportedly 1/2" or 3/4") is inserted in shallow (~50 ft), large diameter (36") boreholes. The configuration of the loop piping is much like a slinky suspended from one end so as to form a cylinder with an outside diameter slightly smaller than the borehole.



The larger diameter and the much lower heat rate through the tube wall and fill material contributes to the potential for enhanced performance relative to conventional U-tubes. The large diameter of the hole could allow the use the native material for fill since there would be less problem with bridging. Since it is difficult to hold the piping evenly distributed against the bore wall, spacers must be used. They must be strong to remain intact during the backfill operation. If the coil piping is separated from the borehole wall or "bunched up", heat transfer will be substantially reduced.

Performance of this configuration and how to evaluate it with available design software is a frequent question. GchpCalc, version 3.1 can, according to the developer, be used to evaluate the borehole design described above. The actual diameter of 36" and a high fill material conductivity (to simulate a low thermal resistance between the pipe and the ground) are input. As an example, a small office building with a peak load of 30 tons and 850 full load cooling hours and 250 full load heating hours was used. Key input values were soil k of 1.2 Btu/hr-ft-F and a ground temperature of 61°F. The following table summarizes the results of both the large borehole design and a U-tube loop design for this building.

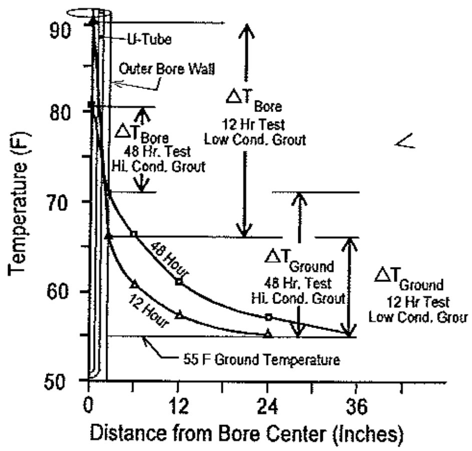
In any situation in which bores are placed in a grid pattern, interference occurs which reduces the effectiveness of the

Continued on Page 2

Design Issues and Tools

Ground Conductivity Testing (Continued)

compared to the soil temperature change (55 to 66.5°F). The relative amount of temperature rise across the ground is much higher for the 48-Hour test with the high conductivity grout. Since the amount of temperature rise in the loop due to the bore hole effects is reduced, the accuracy in deducing thermal conductivity of the soil is improved. Also, the heat has moved farther out into the formation and into soil that has not been disturbed by the U-tube installation. Drilling methods typically inject a drilling fluid (wet clay) or compressed air (warm, dry) into the formation near the bore. The ground near loop must also be given time to recover before the test is started. This is especially true if cement based grouts, which give off heat when curing, are used.



Temperature Profiles in Ground Conductivity Tests

The ASHRAE research project should address these issues. In the interim, the following recommendations are suggested.

1. The heat rates should be near the expected peak loads on the U-tubes (15 to 25 watts per ft. of bore), should be constant and maintained from 12 to 48 hours.
2. The thermal resistance of the bore (pipe & grout) should be minimized so that the measured temperature rise is a strong function of the thermal properties of the soil.
3. The depth of the test bore should be near the expected average length of the ground loop.
4. The test should not begin for 24 hours after the loop has been inserted. This time should be extended for 72 hours if cement based grouts are used.
5. Test times of 36 to 48 hours should be considered if large amounts of drilling mud or air are used during drilling or if low conductivity (< 0.75 Btu/hr-ft-°F) grouts are used.

Correction: The high density polyethylene pipe pressure rating table appearing on page 2 of the Winter 1999 edition of *Outside the Loop* had an error. SDR 13.5 pipe is rated at **111 psig** at 90°F rather than **11 psig** as listed in the Table. Thanks to Toni Boyd of the Geo-Heat Center for spotting the goof.

Large Bore Coils (Continued)

Borehole Length Requirement -Ft/ton (with 80% Diversity)

	Conventional U-Tube 5" Bore, 1" SDR 11		Large Bore 36" Dia., 3/4" DR 11	
	Yr 1	Yr 10	Yr 1	Yr 10
5x6 grid @ 20'	188	220	54	114
1x30 grid @ 20'	186	202	47	66
1x30 grid @ 40'	-	-	42	51

individual boreholes. Heat that cannot be transferred away from an individual bore due to the interference is stored in the ground near that bore. The greater the spacing between the bores and the greater the depth of the bores, the greater is the volume of ground in which this heat can be stored. In cooling dominated climates, an upward temperature "creep" over a period of years will result. If the ground loop design does not take this effect into account, entering water temperatures will rise year by year and compromise system performance. The unusual grid arrangement (1 x 30) and large spacing highlight the sensitivity of these designs to interference between bores.

The software simulates this interference effect by providing two values for the length requirement, one for the first year of operation and one for the 10th year of operation (at which point most systems will have reached thermal equilibrium). The shallow depth of the large diameter design is more strongly influenced by adjacent borehole interference. When spaced at 20ft. in a 5x6 grid, the conventional U-tube design requires 188 ft of borehole per ton to produce an 85°F EWT in the first year and 220 in the 10th year to produce the same EWT. The large diameter design produces the same EWT at 54 ft/ton in year 1 but requires 114 ft/ton in year 10. Orienting the bores in a single row and/or spacing them at 40' reduces the impact of the thermal interference on the large borehole design

In conclusion it appears that the large borehole design does offer the prospect for substantially reduced length requirement relative to the commonly used U-tube arrangement. Design of the ground loop must carefully consider the impact of interference and the installation must be accomplished in a way that does not compromise the position and spacing of the piping. Applications involving soft drilling conditions (with stable borehole walls), and non-grid type ground loops would be most suitable for this design. Due to the heavy impact of interference, designers should not draw conclusions about the performance based on early year data. However, in naturally porous soils, the negative impact of long-term interference is mitigated by water percolation through the formation.

Caution is warranted since major obstacles exist in addition to the heat storage problem. The first problem is increased head loss, which leads to larger pumps and reduced system efficiency. Second, the higher heat rates in the soils may tend to dry the formation and lower conductivity. Thus, rainfall may be necessary to regenerate the loop fields. Finally, if the bores are covered by the same environmental regulations as U-tubes, there will be some very wealthy grout and pipe vendors.

CEMENTITIOUS GROUTS 101

By Marita L. Allan, Brookhaven National Laboratory

Grouts used to backfill boreholes for vertically oriented ground source heat pumps (GSHPs) can be divided into bentonite or cement-based. Concerns have been expressed about shrinkage, excessive heat of hydration and poor bonding to U-loop with some cementitious grouts. By use of fillers and admixtures, together with suitable mix proportioning, the properties of cementitious grouts can be improved. The New Jersey Department of Environmental Protection recently approved use of a superplasticized cement-sand grout for use in consolidated and unconsolidated formations following an injunction on the use of unfilled cement grouts. This article outlines the basics of cementitious grouts.

Materials

In its simplest form cementitious grout consists of ordinary Portland (ASTM Type I) cement and water. This is often referred to as neat cement grout. Variations on the simplest grout include different cement types, addition of bentonite, partial replacement of cement with mineral admixtures (supplementary cementing materials), addition of retarders or accelerators, and use of water reducing agents. Neat cement grouts have relatively low thermal conductivity (typically 0.46 to 0.50 Btu/hr·ft·°F) making their use for GSHP applications limited. By adding filler materials such as silica sand the thermal conductivity can be increased up to 1.1 to 1.5 Btu/hr·ft·°F depending on proportion.

The properties of cement grouts are controlled primarily by the water/cement ratio. This includes viscosity, hydraulic conductivity, strength, durability, and shrinkage. Thermal conductivity is also affected by water/cement ratio, particularly if the grout dries out since excess water is evaporated and the resultant porous material has a lower thermal conductivity. A good quality cementitious grout requires minimization of the water/cement ratio.

The behavior of fresh, or unhardened, grout is critical since this will determine the ability to mix, pump and place the grout with conventional equipment. In addition to the strong influence of water/cement ratio, the viscosity of grout can be altered through the use of chemical admixtures. Water reducing and superplasticizing (high range water reducing) agents can be used to reduce the water demand while retaining low viscosity. Consequently, the water/cement ratio can be reduced and this is beneficial for such properties as thermal conductivity, shrinkage resistance, strength, hydraulic conductivity and durability. Superplasticizers are more effective than regular water reducers. These admixtures are covered in ASTM C 494 and ASTM C 1017. The effectiveness of superplasticizers decreases with mixing time. The sequence of superplasticizer addition also exerts a significant effect on grout rheology. Superplasticizers can act to increase bleed and shrinkage, particularly if overdosed.

Many groundwaters and soils contain levels of soluble sulfates that are detrimental to the integrity of Type I cement-based materials. This potential problem can be overcome either through partial replacement of Type I cement with, for example, blast furnace slag or by substitution with a sulfate resistant cement (Type II or V).

Bentonite (impure sodium montmorillonite) is a common additive and is used primarily to improve grout stability, reduce bleeding and reduce segregation of sand. Apparent viscosity and cohesion increase with increasing bentonite content. Superplasticizers have reduced effect with high bentonite content grouts. High proportions of bentonite increase set time and reduce the strength of grouts. Bentonite can be difficult to mix uniformly with water, particularly when using a paddle mixer as is common in the GSHP industry. Use of a high shear mixer may obviate the necessity for bentonite and this is discussed further below.

In addition to increasing thermal conductivity, sand also has the benefit of reducing shrinkage and improving mechanical properties for equivalent water/cement ratios. Cement-sand grouts have lower heat of hydration when compared with neat cements. It is important that silica sand used to enhance thermal conductivity and impart other beneficial properties to grout should consist of a wide and well-graded range of particle sizes and be well rounded as opposed to angular or flaky. Sand that is too coarse will tend to segregate and cause pumpability problems whereas very fine sand will increase the water demand and limit the proportion of sand that can be added to the grout. The exact gradation of sand that can be used successfully in grout will depend on the mixing and pumping equipment. Research at BNL has found that sand between 75 μm and 2.36 mm (Sieve Numbers 200 to 8) works well with a superplasticized cement grout mixed in a paddle mixer. This is similar to concrete sand except that the coarse material (i.e. retained on Number 8 and 16 sieves) is not used. Use of mineral admixtures such as silica fume, fly ash or blast furnace slag may alter the gradation and proportion of sand that can be used.

Mixing and Pumping

The GSHP industry tends to use low shear, paddle mixers for mixing grouts. The order of addition for cement-sand grouts with this type of mixer is typically water, bentonite, superplasticizer, cement and sand. It is more common in the geotechnical and structural grouting arenas to use high shear or colloidal mixers. These are more efficient than paddle mixers and may permit reduction of water/cement ratio, decreased superplasticizer dosage and increased sand proportion. Also, it may be possible to omit bentonite in the grout formulation with such a mixer. In either case, it is preferable to use a grouting unit that consists of a mixer and a separate agitator tank. With this arrangement grout is transferred from the mixer to the agitator tank where it is continuously stirred as it is stored or pumped. It is important to always keep the grout moving as cementitious grouts, particularly those containing bentonite, tend to be thixotropic and will form a gel on standing. Furthermore, keeping the grout mobile prevents segregation of sand. The use of an agitator tank simplifies this requirement.

Cement-sand grouts are best pumped with either piston or ram type pumps. Progressing cavity pumps may experience excessive wear. A 1¼" tremie tube is recommended for cement-sand grouts. The grout must be placed from bottom to top and the tremie tube must always be kept below the surface of the grout as it is withdrawn.

Quality Control

Every batch of freshly mixed grout should be measured for specific gravity prior to pumping. This requires use of a mud balance available from companies such as Baroid and the test procedure is given in ASTM D 854-83. The specific gravity is sensitive to water/cement ratio, sand/cement ratio and uniformity of mixing. Measuring flow time in accordance with ASTM C 939 can also be performed to check for grout pumpability and uniformity

It is recommended that samples of grout should also be taken for future laboratory thermal conductivity testing. The grout should be poured into a leakproof container, the dimensions of which depend on the equipment that will be used to measure thermal conductivity. The grout samples should be sealed or covered with plastic for 24 hours and maintained at temperature as close as possible to 20-25°C. After 24 hours the samples should be demoulded and immersed in a water bath at 20-25°C to cure for at least 7 days prior to testing.

General Information on Cementitious Grouts

- Kosmatka, S.H., Cementitious Grouts and Grouting, Portland Cement Association, 1990.
- Domone, P.L.J. and Jefferis, S.A. (Eds), Structural Grouts, Blackie Academic and Professional, Cambridge, 1994.
- Houlsby, A.C., Construction and Design of Cement Grouting, John Wiley and Sons, New York, 1990.

Information on Cementitious Grouts for GSHPs

- M.L. Allan, Thermal Conductivity and Other Properties of Cementitious Grouts, International Ground Source Heat Pump Association Technical Conference, Stillwater, May 1998.
- M.L. Allan and S.P. Kavanaugh, "Thermal Conductivity of Cementitious Grouts and Impact on Heat Exchanger Length Design for GHPs", *International Journal of HVAC&R*
- S.P. Kavanaugh and M.L. Allan, "Testing of Enhanced Cement Ground Heat Exchanger Grouts", *ASHRAE Transactions*, Vol. 105, Pt. 1, Atlanta, 1999.
- M.L. Allan, "Thermal Conductivity of Cementitious Grouts for Geothermal Heat Pumps", FY 97 Progress Report, BNL 65129, Nov. 1997.
- M.L. Allan and A.J. Philippacopoulos, Thermally Conductive Cementitious Grouts for Geothermal Heat Pumps: FY 98 Progress Report, BNL 66103, Nov. 1998.

Recipes of Thermally Enhanced Grouts

Cement based grouts

54 lbs. Cement + 200 lbs. Silica Sand* + 1.04 lbs. of 200 mesh Sodium Bentonite + 21 Fl. ounces of Superplasiczer + 6.2 Gal. of Water   19 gal. of grout with a TC of **1.4 Btu/hr-ft-F.**

*Sand Gradation for Cement-Based Grouts

Sieve No. Size (μm)	8 (2360)	16 (1180)	30 (595)	50 (297)	100 (149)	200 (75)
Percent Passing	100	95-100	55-80	30-55	10-30	0-10

Bentonite based grouts

50 lbs. Bentonite + 23 gallons of Water   27 gallons of grout 20% solids with a ther. cond. (TC) of **0.43 Btu/hr-ft-F.**

54 lbs. Bentonite + 100 lbs. Silica Sand* + 15 gallons of Water   24 gal. of 58% solids grout with a TC of **0.65 Btu/hr-ft-F.**

54 lbs. Bentonite + 200 lbs. Silica Sand* + 17.5 gal. of Water   30 gal. of 64% solids grout with a TC of **0.85 Btu/hr-ft-F.**

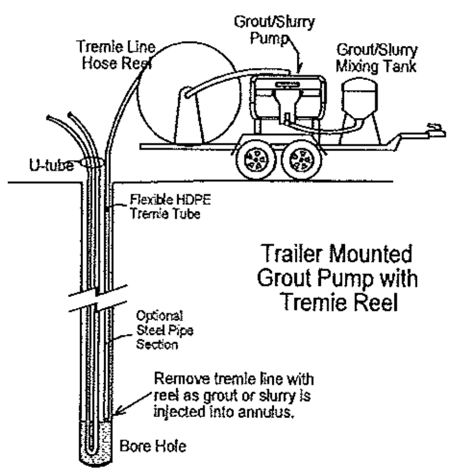
54 lbs. Bentonite + 350 lbs. Silica Sand* + 21.5 gal. of Water   41 gal. of 69% solids grout with a TC of **1.15 Btu/hr-ft-**F.

54 lbs. Bentonite + 600 lbs. Silica Sand* + 25 gallons of Water   56 gal. of 76% solids grout with a TC of **1.45 Btu/hr-ft-F.**

*Sand gradation varies by manufacturer.

Volume Required to Backfill U-Tube Boreholes
Gallons per 100 Feet of Bore Hole

	Diameter of Bore							
U-tube Dia.	3.5"	4.0"	4.5"	5.0"	5.5"	6.0"	6.5"	7.0"
3/4"	**41**	**56**	**74**	**93**	**114**	**136**	**163**	**191**
1"	-	**51**	**69**	**88**	**109**	**133**	**154**	**186**
1-1/4"	-	-	**60**	**80**	**101**	**124**	**150**	**177**
1-1/2"	-	-	-	**73**	**94**	**117**	**143**	**170**



Products, Services, and Installation Innovations

Commercial Building GCHP Loop Contractors

Please send names of other commercial GHP contractors.

A&E Drilling Services, Greenville, SC 864-288-1986
Ash Drilling, Lebanon, TN, 615-444-0276
Ball Drilling, Austin TX, 512-345-5870
Bergerson-Caswell, Maple Plain, MN 612-479-3121
Bertram Drilling, Billings, MT (and PA), 406-259-2532
Harvey Cain Drilling, Atlanta, TX 903-796-6339
Can-America Drilling, Simla, CO 80835, 719-541-2967
Closed Loop Systems, Tallahassee, FL, 850-942-7668
Craig Test Boring, Mays Landing, NJ, 609-625-4862
Douglas Exploration, Douglas, WY, 307-358-3125
Donamarc Geothermal, Union Town, OH, 330-896-4949
Earth Energy Engineering, Big Stone Gap, VA 540-523-2283
Energy Systems, Pensacola, FL, 850-456-5612
Enviro-Tec, Cresco, IA, 800-728-6187
Ewbank & Associates, Enid, OK, 405-272-0798
Falk Brothers, Hankinson, ND 701-242-7252
Geo-Energy, Vermillion, SD, 605-624-6745
Geo-Therm Heating-Cooling, Alexandria, KY, 606-635-7442
Geo-Systems Inc., Wallingford, KY, 606-876-4621
GeoMasters, Newton, TX 409-379-8537
Georgia Geothermal, Columbus, GA, 800-213-9508
Geothermal Drilling, Huntsville, TX, 409-293-8787
Geothermal Drilling, Louisville, KY 502-499-1500
Geothermal Services, Mays Landing, NJ 877-394-4689
Geothermal Energy Management, Savannah, GA,912-964-7486
Ground Source Systems, Buffalo, MO, 417-345-6751
Frame Drilling, Elkins, WV, 304-636-6025
Hammett & Hammett, Andalusia, AL, 334-222-3562
Henry Drilling, Franklin, TN, 615-794-1784
Jedi Drilling, Cibilo, TX, 210-658-7063
Johnson Drilling Co., Dallas, TX 972-924-2560
K & M Shillingford, Tulsa, OK, 918-834-7000
Layne-Atlantic, Suffolk, VA 757-934-8971
Loop Master, Indianapolis, IN, 317-872-3766
Loop Tech International, Huntsville, TX, 800-356-6703
Mid-America Drilling, Oakland, IA 712-482-6911
Mid-State Drilling, Livingston, TN, 931-823-7345
Middleton Geothermal, Akron, OH 330-620-0639
Mineral Services Plus, LLC, Cologne, MN 612-446-5503
Morrison Inc., Duncannon, PA 717-834-5667
Moses Drilling Co., Gray, KY, 606-523-1215
Murray Drilling Corp., Princeton, KY, 502-365-3522
Neese Jones Heating-Cooling, Alpharetta, GA, 770-751-1850
Larry Pinkston, Virginia Beach, VA, 804-426-2018
Pruitt Drilling, Moab, UT, 435-259-6290
Reith Brothers Well-Drilling, Emmaus, PA 610-965-5692
Richard Simmons Drilling, Buchanan, VA 540-254-2289
Rock Drillers, Inc., Bardstown, KY, 502-348-6436
Saathoff Enterprises, Bruce, SD, 605-627-5440
Somerset Well Drilling, Westover, MD, 410-651-3721
Thermal Loop, Joppa, MD 410-538-7722
Venture Drilling, Inc. Tahlequah, OK 918-456-8119
Van and Company, Duncan, OK, 580-252-2205
Virginia Energy Services, Richmond, VA, 804-358-2000

More Contractors

Pointy-Headed Professor & Friends Descend from Ivory Tower and Go Below $10/ft^2 Barrier

Chuck Remund is a professor of Mechanical Engineering at South Dakota State University and he will do just about anything to get someone to use ground source heat pumps. He has trained contractors, done research, argued, taught classes, written papers, indoctrinated his 7-year old son, argued some more, sold thermal grout, coerced a fellow professor to design ductwork and stamp drawings, and talked a guy out of a comfortable (but boring), high-paying job to start a geo-company to put in twice as many hours for less pay.

The company, GRTI, has even done some engineering design work. One example of a recently completed project dipped well below the magical $10/ft^2 barrier. The facility is a 26,000 ft^2, 58-ton athletic facility in Sisseton, SD, which consists of a double gym, weight room, wrestling room, and two locker rooms. The ground loop is 39 bores at 200 ft. each grouted with thermally enhanced bentonite (of course). Ventilation air is heated by electric resistance with SCRs controllers, which use input from four CO_2 sensors. The cost summary was:

Ground Loop	$ 54,600
Heat Pumps (58 Tons)	38,800
Duct Work	50,000
Piping/Insulation	6,500
Pumps	4,500
Ventilation Units	3,800
Electric Heaters (70 kW)/Cabinets	5,100
CO_2 Sensors (4)	4,800
Grills, Louvers & Registers	6,000
Exhaust Fans	1,200
Labor	25,000
Taxes	6,600
Total	**$ 206,900**
$/ft^2	**$ 7.96/ft^2**
$/ton	**$ 3,567/ton**

Innovations Displayed at IGSHPA Conference

Call 800-626-4747 for a list of vendors at the conference.

- U-tube Spring Clips to push HDPE tubes to outer bore wall and reduce thermal resistance caused by low TC grout.
- Enhanced bentonite grouts (TCs = 0.65 to 1.45 Btu/hr-ft-F)
- Circulator pumps with epoxy coated housings & impellers.
- Higher efficiency heat pumps
- Improved pump for thermally enhanced grouts.
- All HDPE vault/header for large loop fields and Quick-Connects for heat recovery units with PEX tubing.
- Pre-fabricated HDPE piping networks

More Loop Contractors

Virginia Service Co., Virginia Beach, VA, 757-468-1038
Winslow Pump & Well, Hollywood, MD, 301-373-3700
Yates & Yates, Columbia, KY 502-384-3656

Letters, Comments, Questions, & Suggestions

To Insulate or Not to Insulate? (Interior GCHP Pipe)

We have been installing GCHP systems in the Austin area for a number of years without insulating the interior piping. The loops are warm in the summer and are never below 50°F in the winter. Is it necessary to insulate the lines above the ceilings to prevent moisture condensation?

Should I be worried in Texas?

Dear Should I,

The cooling mode temperatures of GCHP piping in southern climates are well above the dew point temperature of the room air. So there should be no condensation of water on the outside of uninsulated piping during the cooling season. The period of concern is during the winter operation when the loop temperature is 50°F or less. If high-density polyethylene (HDPE) is used, moisture condensation is unlikely on uninsulated piping with normal room air conditions with loop temperatures above 45°F. Metal piping should be insulated if temperatures are below 50°F. Here is an example calculation that your design engineer should be able to perform.

A 4-inch, SDR 11 HDPE pipe carries 50°F water through a room at 70°F/50% relative humidity. Is insulation necessary to prevent condensation?

A psychrometric chart indicates the dew point temperature of the room air is 50°F. Therefore, if the outside temperature of the pipe wall (t_o) is less than this value, condensation will occur. To determine the pipe wall temperature, first find the heat loss per unit length of pipe.

$$q/L = \frac{t_{room} - t_{water}}{R_i + R_p + R_o} \quad where\ R_i << R_p \ \&\ R_o,$$

$$R_p = \frac{\ln d_o/d_i}{2\pi k_p} = \frac{\ln 4.5''/3.68''}{2\pi\ 0.22 \frac{Btu}{hr-ft-F}} = 0.146 \frac{hr-ft-F}{Btu}$$

$$R_o = \frac{1}{h_o \pi d_o} = \frac{1}{1.5 \frac{Btu}{hr-ft^2-F}\ \pi \frac{4.5''}{12\ in/ft.}} = 0.566 \frac{hr-ft-F}{Btu}$$

$$Thus\ q/L = \frac{70-50°F}{0.146+0.566} = 28 \frac{Btu}{hr-ft}$$

The temperature of the outside pipe wall is,

$$t_o = t_{room} - q/L \times R_o = 70°F - 28 \frac{Btu}{hr-ft} \times 0.566 \frac{hr-ft-F}{Btu}$$

$t_o = 54°F$. *Too warm for condensation!*

Note: This example calculation is conservative since indoor humidity levels during cold weather will likely be lower than 50%. Thus, dew point temperatures will be lower than 50°F.

Well Pumps – Lineshaft or Submersible

We are designing an open loop system for an office building in Nebraska. It is a 225-ton system and we will be pumping approximately 340 gpm. Static water level in the well is 76 feet. Our pump rep is suggesting that we use a lineshaft driven pump. We were planning on a submersible. Can you comment on the relative advantages/disadvantages of the two types?

Picking Pumps in Plattsmouth

Dear Picking Pumps,

Either type of pump could be used in this case but it is likely that the submersible will be less expensive. Lineshaft pumps are generally suited to large industrial/municipal applications at high (>350 - 400 gpm) pumping rates. They are somewhat more efficient than submersibles but not sufficiently so to impact the decision. Lineshaft pumps rotate at slower speeds (nominal 1800) compared to submersibles (3600) and as a result are more tolerant of sand. Due to the long rotating shaft connecting the motor and the bowl assembly, a straighter well is required and this should be reflected in a tighter specification for plumbness and alignment in the well specification. At the static water level in your well, an open type lineshaft should not be used. To assure adequate lubrication at start up an enclosed lineshaft (with water or oil lubrication) should be used. As a result of the above ground motor location, wells with lineshaft pumps are normally equipped with well head structures for protection of the motor.

Submersible well pumps are the choice for most GSHP applications. For the flow rates involved in these systems they are typically 20% to 50% less first cost than lineshaft pumps and they require no surface structure. Rotating at a nominal 3600 rpm they are more sensitive to sand in the production stream than lineshaft pumps. If variable speed is to be used, submittals verifying the motor manufacturer's awareness of this fact should be required. It may be necessary to equip the motor with an auxiliary cooling shroud and electronic compensation for drive-to-motor length may be necessary depending upon depth. Submersibles are more voltage sensitive than surface motors and cable selection should be carefully considered. Submersibles should always be equipped with a foot valve to assure that the motor starts under load (full column of water). This prevents momentary thrust reversal that can damage the motor.

Obviously, the nature of the submersible precludes any routine maintenance since all the components are below grade. Regular monitoring of motor current is advisable for both submersible and lineshaft equipment. For systems served by a single well it is useful to store a spare pump and motor on site for submersibles or a spare pump (bowl assembly) for lineshaft type pumps.

Meetings, Publications, and Information Sources

Meetings & Seminars - 1999

May 30-June 2 Heat Pumps - A Benefit for the Environment, 6th International Energy Agency (IEA) Heat Pump Centre Conference, Berlin, *sl@vwew.f.eunet.de* or +49-69-6304460

June. 3-4, Two-Day Seminar for Engineers, Portland, OR

June 19-23 -- ASHRAE Annual Meeting, Seattle, WA, 404-636-8400

August 1-3 – Architect & Engineer Seminar, Holiday Inn, Gatlinburg, TN, (7.75 LUs & 7.75 – 9.3 PDHs), 606-367-5839

August 23-25 – Energy '99: An Energy Efficiency Workshop & Exposition, FEMP, DOD, GSA – 800-395-8574, *www.energy.ee.doe.gov*

Sept. 26-29, 1999 Annual GeoExchange Conference & Expo, Sacramento, CA, IGSHPA, 800-626-4747

Oct. 20-22, Geothermal Heat Pump Consortium Annual 1999 Meeting (with the AEE World Energy Engineering Congress), Atlanta, GA 888-255-4436 or 202-508-5500

Publications

ASHRAE (404-636-8400) web site: www.ashrae.org

Operating Experiences with Commercial Ground-Source Heat Pumps, (Case Studies), 1998

Ground-Source Heat Pumps: Design of Geothermal Heat Pump Systems for Commercial/Institutional Buildings, 1997

Commercial/Institutional Ground-Source Heat Pump Engineering Manual, 1995

Thermal Properties & Estimation Techniques for GCHP Bore Grouts and Fills
(Symposium Papers from 1999 Winter Annual Meeting)
Borehole Thermal Resistance: Laboratory & Field Studies
Testing of Thermally Enhanced Cement GCHP Grouts
Borehole Grouting: Field Studies & Thermal Performance
Determining Soil Formation Properties from Field Data

Operating Experiences with Commercial Ground-Source Heat Pumps, 863RP (Research Project Report), 1995

Electric Power Research Institute (510-934-4212)

Heat Pump News Exchange – Quarterly Newsletter

"Grouting for Vertical GHP Systems: Engineering Design Guide and Field Procedures Manual", Report # TR-109169

Geo-Heat Center (541-885-1750) www.oit.edu/~geoheat

"Outline Specifications for Water Wells and Pumps", 1998.

"A Capital Cost Comparison of Commercial Ground-Source Heat Pump Systems", 1994.

"An Information Survival Kit for the Prospective Geothermal Heat Pump Owner", 1997 - RESIDENTIAL

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Heat Pump Systems for Single Room Applications" (Workshop Proceedings - Dec. 1998, Final Report - Jan. 1999)
http://www.heatpumpcentre.org

Geothermal Heat Pump Consortium (888-255-4436)
www.ghpc.org

GeoExchange Site List – A list of commercial and institutional GHP buildings in North America (RP-011)

GeoExchange Material and Publications – A list of materials and publication available through the GHPC (RP-015)

"Development of Head Loss Data and Design Tools for GHP Piping", 1996 (RP-017) – Includes Piping Design Software

"Maintenance and Service Costs in Commercial Building Geothermal Systems", 1997 (RP-024)

Analysis of Existing GeoExchange Installation Data (RP-026)

Icemakers, Coolers & Freezers, and GX – A survey of water requirements for refrigeration equipment. (RP-030)

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The Source - IGSHPA Newsletter

Grouting for Vertical GHP Systems: Engineering and Field Procedures Manual, 1997 (a.k.a. EPRI Report # TR-109169)

National Ground Water Assoc. (800-551-7379)

"Guidelines for the Construction of Vertical Bore Holes for Closed-Loop Heat Pump Systems", 1997 (Also available from EPRI)

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A Newsletter for Geothermal Heat Pump Designers and Installers

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- Developments in Ground Property Testing
- Large Diameter Bore Coils
- Basics of Enhanced Cement Grouts
- Recipes of Thermally Enhanced Grouts
- Letters – Insulated Interior Piping
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GEOEXCHANGE

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PERFORMANCE CHARACTERISTICS AND MODELLING OF CEMENTITIOUS GROUTS FOR GEOTHERMAL HEAT PUMPS

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Key Words: geothermal heat pumps, grouts, thermal conductivity, heat transfer, thermal stresses, deformations.

ABSTRACT

The objectives of this work are to develop, characterize and model the behaviour of thermally conductive cementitious grouts for use with geothermal heat pump systems. The grouts have been tested for thermal, hydraulic, mechanical and other properties. The mean thermal conductivity of a grout formulation with 2.13 parts of sand to one part of cement by mass was 2.42 W/m.K. This is up to three times higher than bentonite grout and has a significant impact on lowering the overall thermal resistance. The mean coefficient of permeability for the same grout was 1.6 x 10^{-10} cm/s. When polyethylene pipes representing a U-loop heat exchanger were included in the system the mean coefficient of permeability increased to 1.9 x 10^{-7} cm/s due to imperfect interfacial bonding. Infiltration tests on grouted U-loops were conducted and the effect of circulating fluid temperature was measured to determine the efficacy of the grout for sealing boreholes. The infiltration rate remained of the order of 10^{-7} cm/s when fluid temperature was varied from 3 to 35°C demonstrating that the grout sealing performance was not significantly impacted. Finite element analysis was employed to evaluate the temperature distribution and the corresponding stresses and deformations developed within a grouted borehole as well as in the surrounding formation. The models developed incorporate all major components of the system (pipe/grout/formation). Heat transfer analysis was performed to evaluate the temperature distributions for the cooling and heating modes of operation. This task was followed by a thermal stress analysis.

1. INTRODUCTION

Boreholes used with closed loop vertical heat exchangers for geothermal heat pumps (GHPs) are grouted to meet performance and environmental requirements. The grouting material promotes heat transfer between the heat exchanger and the surrounding media and forms a hydraulic seal to protect aquifers from contamination. Traditionally, bentonite and neat cement (water plus cement) grouts have been used for this purpose despite the relatively low thermal conductivity and tendency to shrink and crack on loss of moisture. Furthermore, bonding to polyethylene pipes (U-loop/U-tube) is relatively poor for these materials. In response to these deficiencies research has been directed at development, testing and analysis of cementitious grouts that offer several significant benefits over conventional materials in terms of heat transfer, impermeability, dimensional stability, durability and cost effectiveness.

The numerical modelling component of the research involves analysis of several performance related issues. These include impact of contact resistance on heat transfer, effect of boundary conditions on temperature distribution within the grout and prediction of thermally induced stresses and deformations in the grout. A detailed two-dimensional finite element model of the ground heat exchanger has been developed which incorporates both pipes, grout and surrounding formation. The model permits a direct definition of heat sources and pertinent boundary conditions for the heat transfer and thermoelastic asymmetric problems. In addition, the model allows for simulation of air or water-filled gaps at the grout/U-loop interfaces which are considered in ongoing research. The thermal stresses and deformations developed in the ground heat exchanger have been analyzed for both heating and cooling modes of operation.

This paper describes the thermal and hydraulic properties of selected grout formulations and finite element analysis of heat transfer and thermal stresses. The hydraulic properties are important from an environmental perspective. Further details of the grout optimization and other properties can be found in Allan (1997), Allan and Philippacopoulos (1998) and Allan and Kavanaugh (1999).

2. MATERIALS

The basic cementitious grouts consisted of Type I (ordinary Portland) cement, silica sand between 75 and 1180 µm, bentonite, water and superplasticizer. The superplasticizer used was a liquid solution with 42% sodium naphthalene sulphonate by mass. This acts as a dispersant and improves grout pumpability. Variations on the basic mix included partial replacement of cement with fly ash or ground granulated blast furnace slag (BFS). The final mix represented a compromise between performance, cost, simplicity and compatibility with mixing equipment typically used in the US GHP industry. The sand/cement ratio was based on using one 42.6 kg bag of cement to two 45.3 kg bags of sand. The mix proportions and specific gravity of the superplasticized cement-sand grout (Mix 111) are presented in Table 1. Selected properties were measured on grouts with the same mix proportions except for 40% replacement of cement by mass with either ground granulated blast furnace slag (Mix 114) or fly ash (Mix 115).

3. EXPERIMENTAL PROCEDURES

3.1 Thermal Conductivity

Thermal conductivity was measured using the hot wire method with a Shotherm QTM-D2 Thermal Conductivity Meter. The grout was cast as blocks 75 mm x 125 mm x 25 mm. The blocks were cured in a water bath for 14 days prior to testing.

3.2 Coefficient of Permeability

Coefficient of permeability was measured on 102 mm diameter cylinders of grout and on grout cast around two lengths of 25.4 mm ID polyethylene pipe to represent a U-loop. The pipes were filled with wax to restrict permeation to either the grout or the grout/pipe interface. The first type of test measured the hydraulic properties of bulk grout. Tests on grout cast around pipes incorporate any preferential flow at the interface between grout and polyethylene. Details of the testing procedure are given in Allan and Philippacopoulos (1998, 1999). A flexible wall triaxial cell permeameter was used. All specimens were cured for 28 days in water and vacuum saturated before testing at 21°C.

3.3 Infiltration Rate

Infiltration tests were performed to measure penetration of a head of water above grouted tubes containing a U-loop. At this stage only infiltration through the grout and at the grout/ U-loop interfaces has been considered. The test configuration was similar to that used by Edil et al. (1992) to study the sealing characteristics of different grouts for water wells. The experimental arrangement consisted of two PVC tubes each containing a U-loop. The tubes were 80 cm long and 102 mm internal diameter. Grout was tremied from the bottom up into the tubes using a 25.4 mm diameter tremie tube. A second PVC tube was glued to the top of each of the grouted tubes. The top tube was filled with water to give an initial head of 29 cm. A graduated burette was attached for viewing water elevation. The infiltration rate was calculated as the change in elevation with time.

The grout was allowed to cure for 28 days. Infiltration proceeded at room temperature for the first 68 days. Water at a temperature of 35°C was then circulated at a flow rate of 5.7 l/min through the U-loops for three weeks and infiltration rate was monitored. Following this, the circulating water temperature was decreased to 3°C for a further three weeks. The hot and cold temperatures of circulating water in the loops simulated operation of a heat pump in cooling and heating modes, respectively. It is recognized that operational temperatures may be outside the test range in some circumstances. The experiments enabled the effect of thermal expansion and contraction of the U-loop on infiltration rate to be determined. Due to the relatively short length of the U-loops, the inlet and outlet water temperatures were equal. Thus, the temperature gradient between loop legs that would occur in practice was not reproduced. If infiltration rate is controlled primarily by flow at the grout/U-loop interfaces and this, in turn, depends on differential thermal expansion and contraction of the system components then variation between experimental and field infiltration rates can be expected. It is predicted that the experimental infiltration rates will be lower than when hot water circulates and higher when cold water circulates since both pipes are expanding or contracting the same amount rather than differential deformations that occur with a temperature gradient.

Heat transfer between the U-loop and head of water resulted in temperature changes in the infiltrating water. The temperature of the water head was 33 and 8°C for the cooling and heating mode tests, respectively, and this must be taken into consideration when analyzing the results. In order to account for volume changes in the head of water associated with thermal effects, the changes in elevation were measured at equal temperatures so that the influence was constant.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The average thermal conductivity of the Mix 111 grout when mixed under laboratory conditions was 2.42 W/m.K in the saturated state and 2.16 W/m.K when oven dried. This compares with 0.75 to 0.80 W/m.K for high solids bentonite and 0.80 to 0.87 W/m.K for neat cement grouts. Higher conductivity can be expected to enhance heat transfer and performance of the GHP. Furthermore, increased conductivity permits reduction of required bore length and, hence, decreased installation costs (Allan, 1997; Allan and Kavanaugh, 1999). Field mixed grout had an average thermal conductivity of 2.19 W/m.K in the saturated state. The lower conductivity may be due to lack of wet curing.

The results of the coefficient of permeability tests are given in Figure 1. The bulk Mix 111 grout had relatively low permeability coefficient of the order of 10^{-10} cm/s. Addition of fly ash to the grout increased permeability whereas blast furnace slag had a negligible effect for the curing period of 28 days. The coefficient of permeability increased significantly when ,polyethylene pipes were included in the system. However, the results were within the target order of 10^{-7} cm/s. The mean values were 1.9×10^{-7}, 2.4×10^{-7} and 5.3×10^{-7} cm/s for Mixes 111, 114 (slag-modified) and 115 (fly ash-modified), respectively. The increase is due to imperfect bonding between the grout and polyethylene. Incorporation of fly ash in the grout resulted in higher permeability coefficient and correlated with larger interfacial gaps. Although fly ash offers potential cost reductions, lower heat of hydration and improvement in durability, the negative impact on bonding is a concern for both environmental protection and heat transfer performance.

The mean infiltration rate data for the two grouted tubes is presented in Figure 2. The time interval for each data point was 7 days. There was no outflow for the system and, therefore, it was not possible to calculate falling head permeability. The graph shows that infiltration at ambient temperature decreases with time to steady state values. This is associated with ongoing cement hydration and consequent pore refinement. Circulation of hot or cold water caused temporary increases in mean infiltration rate and there was no consistent trend throughout the thermal cycles. Thus, it appears that there may be other effects controlling infiltration rate besides thermal expansion and contraction of the U-loop. The changes in temperature of the head of infiltrating water may have been influential due to corresponding changes in viscosity although this does not explain variations during a particular cycle. The infiltration rate remained of the order of 10^{-7} cm/s and the sealing capability of the Mix 111 grout was not significantly compromised by elevated or decreased temperature circulating fluid for the test conditions and duration.

It is recommended that the infiltration rate on full scale grouted boreholes be measured during heating and cooling modes in order to include the interfacial conditions between grout and surrounding formation and the effect of temperature gradients.

5. MODELLING APPROACHES

The steady state and transient heat transfer in vertical U-loop configurations of GHPs has been tackled both analytically and numerically. Analytical modelling is primarily based on line and cylindrical heating source solutions. Several works in this area are based on the early solutions by Carslaw and Jaeger (1940) and later on by Jaeger (1942). Cane and Forges (1991) present a review of such models as they apply to problems related to heat pump configurations.

What made single source models applicable to U-tube thermal analysis was the concept of "equivalent diameter". Note that the presence of two legs in the U-loop generally requires non-symmetric solutions. Accordingly, Claesson and Dunard (1983) using superposition of two single sources to simulate the two pipes of the loop respectively extended earlier single source models. The use of the equivalent diameter is very attractive because it combines the two legs into one and therefore one can use available solutions from line or cylindrical source models thus avoiding complicated asymmetric solutions. Several studies, however, such as that by Mei and Baxter (1986), have shown that a large scatter in data exists. Lack of high confidence data has led the engineering community to doubt this modelling approach and find it not completely satisfactory. Specifically, there are concerns whether such an approach is valid over the range of parameters considered in GHP designs. Recently, the issue of the equivalent diameter was revisited by Gu and O'Neal (1998a). They point out that some of the discrepancies found before could be due to obtaining such values from steady-state solutions and then applying them to transient ones. They also conclude that the ratio of the equivalent diameter to the tube diameter can be two or greater.

Because simple analytical models were derived by assuming line and cylindrical sources in uniform spaces, they cannot take into account fundamental non-homogeneities existing in GHPs. Of primary importance is a material contrast between the grout and the surrounding formation. Even if one feels comfortable using an equivalent diameter, the impact of the grout on the heat transfer cannot be taken into account by such models. That is, the assumption that the heat transfer problem is symmetric may be acceptable in certain cases for simplicity. However, the assumption of homogeneous medium around the axis of the ground heat exchanger is not valid when the grout and the surrounding formation have distinct different material properties. Recognizing this difficulty, Gu and O'Neal (1995) developed an analytic solution for the transient heat transfer problem related to a cylindrical heat source in a nonhomogeneous medium. They used this solution later on (1998b) to evaluate grout effects on GHPs. It appears that the latter work represents the latest state-of-the-art in the domain of analytical modelling of GHP U-tubes. Obviously, none of the existing analytic models are non-symmetric per geometrical and thermal loading requirements of the problem. Thus, it is recommended that the latter requirements be considered in future research in the area of analytical modelling of U-tube ground heat exchangers. This can be done using appropriate Green's functions associated with explicit transient heat transfer solutions. Such models can be then employed with boundary element methods. Furthermore, they can provide essential tools to be used for benchmarking and verification of existing numerical modelling techniques.

A variety of numerical models were developed to overcome the limitations of existing analytic models. They are mostly of the finite difference type. There are very limited studies using finite element models available in the literature. Muraya (1994) used a two-dimensional finite element model to study the transient heat transfer in U-tube vertical heat exchangers of GHPs. Some benchmark problems were utilized for verification purposes. They include both steady state as well as transient heat transfer solutions from single and dual source configurations. Thermal short circuiting between adjacent tubes was investigated using this modelling approach. Muraya (1994) extended 2D finite element heat transfer models to include moisture transport on the basis of the Phillip and de Vries (1957) theory and its extension by Hampton (1989). This combination resulted in non-linear transient heat and mass transfer finite element models. They are quite complex and their validity has not been adequately demonstrated. A more recent treatment of the moisture and heat transfer phenomena associated with the response of ground heat exchangers is given by Piechowski (1998)

The majority of existing numerical models of vertical ground heat exchangers of GHPs are based on finite difference techniques. Muraya (1994) and Gu (1995) give a review of such models in their theses. Since then, significant works in the area of finite difference modelling of vertical U-tube ground heat exchangers are those by Rottmayer et al. (1997), and Yavuzturk et al. (1998).

Rottmayer et al. (1997) modelled the system by a combination of cylindrical finite difference grids. They allow for heat transfer to occur radially and circumferentially in the ground. It is further assumed that no axial conduction occurs. The grid resembles 3D effects. A resistance network was considered for both the grout and the surrounding formation, which was used to set up the equations of heat conduction for the entire system. Computation of the transient heat transfer is reduced by 80% when two time steps are employed in the analysis.

The modelling approach by Yavuzturk et al. (1998) is based on an implicit finite volume formulation of the transient heat conduction in the two-dimensional space. The two legs of the U-tube can be simulated using this approach. Several assumptions were made to make the problem manageable. Among them, provisions were made so that the model simulates infinite medium conditions over the timeframe of the solution (constant far-field temperature). In addition, the grid was not sufficient to define directly the pipe elements and consequently the heating source (to simulate heat flux boundary conditions). Because the conduction process is referred to a single polar system it is geometrically difficult to define the input. Despite the number of assumptions made, Yavuzturk et al. (1998) have shown good correlation with temperature predictions from an analytical model. The model is used in conjunction with in-situ measurements of thermal conductivity (Austin et al., 1998).

In conclusion, both analytic and numerical heat transfer models applied to the U-tube ground heat exchangers require further development. In the analytical domain comprehensive exact solutions to the asymmetric 2D problem (including pipes, grout and formation) should be pursued so that available modelling techniques can be validated. In the numerical domain, the focus should be the finite element analysis, thus taking advantage of the significant developments in the last decade in this area.

6. HEAT TRANSFER AND THERMAL STRESSES

While much of the research in U-tube ground heat exchangers has focused on the thermal conductivity of the grout and on predictions of the temperature response, the corresponding thermal deformation and stress fields have not been addressed. Their significance is reflected by the need of the designer to know the strength of the grout and its likelihood to develop thermal fractures.

Finite element analysis was performed to evaluate a) the heat transfer and b) the deformation and stress fields in the complete pipe/grout/formation system associated with U-tube ground heat exchangers. This system is modeled as a two-dimensional medium using 588 elements. Steady state conduction in the system was considered. In order to simulate the required infinite domain using finite models, a parametric investigation was made to define an appropriate far-field radius for the model. It was found that setting the latter at 10 ft produces comparatively good results. The alternative of using infinite elements to simulate infinite boundary conditions was also investigated. Such elements are attached radially to the exterior plane elements of the model. They are producing zero boundary conditions at infinity. A view of the overall FE model is shown in Figure 3 in which the ground heat exchanger portion (pipes plus grout) are depicted with only a part of the formation.

The thermal conductivities of the pipes, grout and formation were: 0.40, 2.42 and 1.73 W/m.K respectively. The entering and leaving water temperatures for the heating mode were: EWT=5°C, LWT=2°C. The corresponding values for the cooling mode were: EWT=30°C, LWT=36°C. These values were taken as worst case averages considering their variation with depth. Additional boundary conditions were imposed for the thermal stress analysis models so that they are adequately constrained. Plane strain conditions were used. Thermoelastic properties considered for each of the materials are: a) pipe: E=1.4 GPa, ν=0.45, $\alpha=2.16\times10^{-4}$ m/m-°C; b) grout: E=13.8 GPa, ν=0.21, $\alpha=1.65\times10^{-5}$ m/m-°C; and c) formation: E=2.0 to 5.5 GPa, ν=0.33, $\alpha=1.65\times10^{-5}$ m/m-°C (E=elastic modulus, ν=Poisson's ratio and α=coefficient of thermal expansion). The results were obtained with the ANSYS code.

The steady state temperature distribution is shown in Figure 4. Since the response inside the borehole is of primary interest, only results within the borehole are displayed. Similarly, thermal stresses for the cooling and heating mode of operations are shown in Figures 5 and 6 respectively. As expected, all results are symmetric with respect to the axis containing the two centers of the pipes. From Figure 4 it can be seen that the temperature distribution within the borehole for both heating and cooling modes of operation is reasonably smooth. A finer discretization was employed to model the grout. Additionally, two layers of elements were used to model the polyethylene pipes. It is because of such modelling provisions that relative smoothness in temperature results was obtained. A finer mesh does not seem to be required for the temperature solutions. However, for thermal stress solutions some additional refinement may be required for areas exhibiting stress concentrations. Specifically, for both modes of operation higher thermal stresses develop in the grout around the pipes. Comparison of Figures 5 and 6 with Figure 4 leads to the conclusion that the stress fields is consistent with those of the temperature. Stresses are especially higher in the grout near the axis of symmetry in the exterior area. This result is consistent with the physics of the problem. It is recommended that the values of the thermal stresses in these particular areas be evaluated using finer grids consistent with standard practice with similar problems. Finally, the model allows for simulation of air or water-filled gaps at the pipe/grout interface. Also the contact between the grout and the formation is under investigation. Such interface conditions are expected to influence the heat transfer process in the pipe/grout/formation system and consequently the corresponding stresses and deformations.

7. CONCLUSIONS

Cementitious grouts can be tailored to meet property requirements for coupling polyethylene heat exchanger loops to surrounding ground in geothermal heat pump systems. Thermal conductivity can be improved by addition of silica sand to the grout. Coefficient of permeability and infiltration tests reveal that the grout acts as an effective sealant. Existing analytic and numerical modelling techniques for heat transfer in U-tube ground heat exchangers require further development to increase the reliability of current designs and system performance predictions. Presently, finite element modelling appears to be the most promising for predicting the response of ground heat exchangers to thermal loading.

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Table 1. Mix Proportions of Cementitious Grouts

	Mix 111	Mix 114	Mix 115
Cement (kg/m^3)	587.7	349.4	346.2
Fly ash (kg/m^3)	0	0	230.8
Blast furnace slag (kg/m^3)	0	233	0
Water (l/m^3)	323.3	320.3	317.3
Sand (kg/m^3)	1251.8	1240.5	1229
Bentonite (kg/m^3)	6.5	6.4	6.3
Superplasticizer (l/m^3)	8.8	8.7	8.7
Specific Gravity	2.18	2.16	2.14

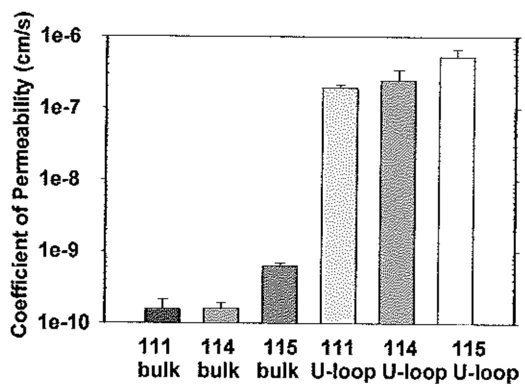


Figure 1. Coefficient of permeability results for bulk grout and grouts cast around U-loop.

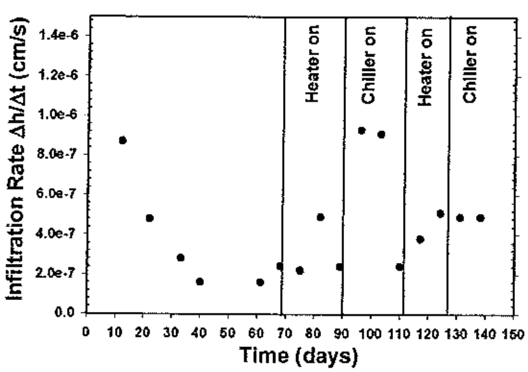


Figure 2. Infiltration rate versus time for grouted tubes.

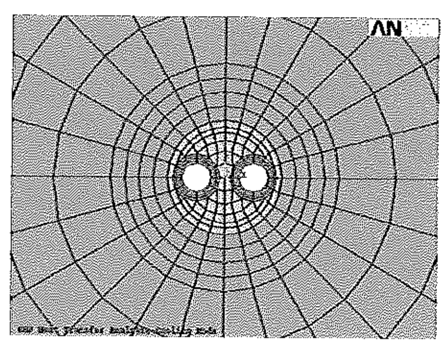
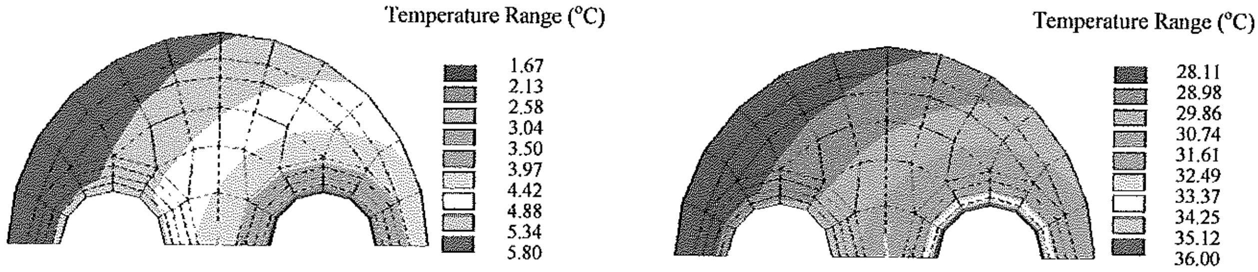


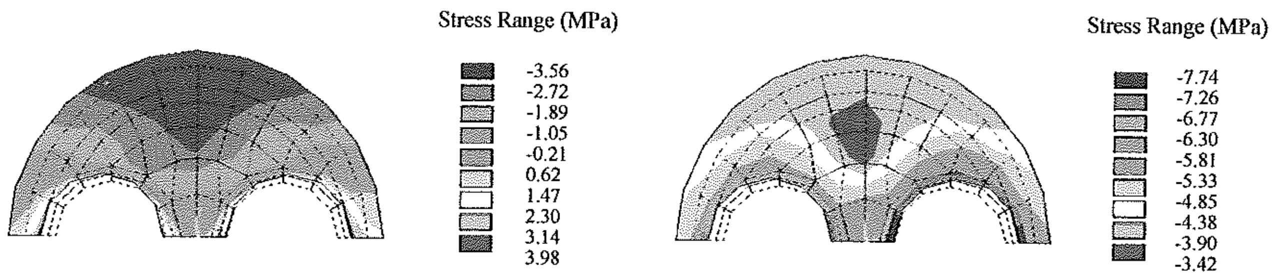
Figure 3. FEM detail near borehole



(a) Heating mode

(b) Cooling mode

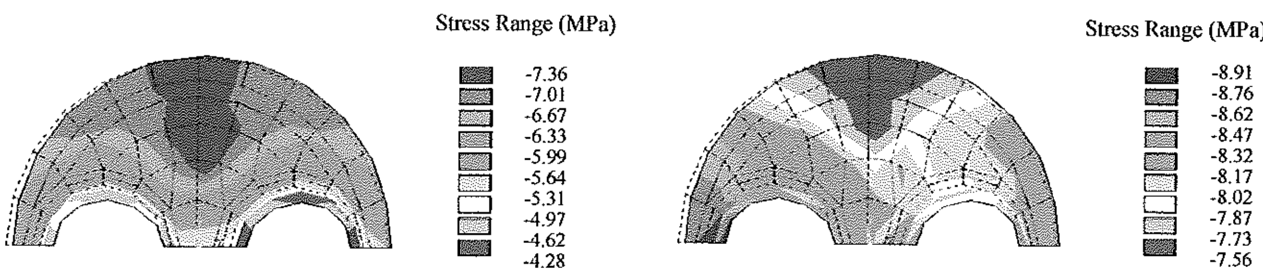
Figure 4. Temperature distribution



(a) Principal stress S1

(b) Principal stress S2

Figure 5. Thermal stresses for cooling mode of operation



(a) Principal stress S1

(b) Principal stress S2

Figure 6. Thermal stresses for heating mode of operation