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**GEOTHERMAL HEAT PUMP RESEARCH AND DEVELOPMENT STUDIES AT
SANDIA NATIONAL LABORATORIES**

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ABSTRACT

The Geothermal Heat Pump (GHP) concept was originally developed in the 1940's. Recently, because of increasing energy costs, utility interest, and the development of simple and durable ground source heat exchangers, GHP's have gained international attention as a proven means of energy conservation and electrical peak power demand reduction. GHP systems require installation of a buried heat exchanger to utilize the nearly constant ground temperature making them more efficient than conventional air source heat pumps. However, the high installation cost for both residential and commercial applications is a major obstacle to their market penetration. Sandia National Laboratories (SNL) through its sponsors, the Department of Energy (DOE) and the Department of Defense (DOD), has

embarked on a research program to find ways to reduce GHP installation costs and improve performance, thereby increasing their market penetration. The major elements of the program are: data acquisition to quantify the performance of GHP's, research and development (R&D) of the ground source heat exchanger aimed at reducing installation costs, and support of DOE efforts to market the GHP concept. This paper describes the current status of our program, some experimental and analytical results, and plans for future activities.

BACKGROUND

There are a wide variety of configurations commonly used to construct a GHP system, some of which are shown in Figure 1. GHP's are technically similar to

Figure 1. Typical Residential GHP Installations.

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conventional freon air conditioners or heat pumps: there is a compressor, expansion valve, air-to-freon heat exchanger and a blower. As in conventional heat pumps, the GHP also has a reversing valve to allow it to supply heat in the winter and cooling in the summer. The difference lies in the heat source or sink external to the conditioned space. Conventional air conditioners and heat pumps use outside air through an air-to-freon heat exchanger. Alternatively, the GHP uses water or anti-freeze circulated through a ground source heat exchanger. Most of these concepts use high density polyethylene pipe as the basis for the ground heat exchanger. This is a very durable, inexpensive pipe with relatively high thermal conductivity. The heat exchanger fluid is circulated with a small pump through a water-to-freon heat exchanger inside the heat pump unit.

The GHP concept has a number of important advantages over conventional alternatives. The GHP unit may be contained entirely inside the heated space and needs no venting. There is no need for above-ground hardware outside the building and all the freon connections in the unit are completed at the factory. There is less freon used relative to conventional air conditioning units or air-source heat pumps because the water-to-freon GHP heat exchanger is much smaller than the outdoor air-to-freon unit needed with air-source equipment. Finally, the warm (cool) temperature of the earth 10 feet or more below the surface relative to the air temperature in winter (summer) significantly increases the capacity and efficiency of GHP's. It also allows GHP's to be effective in a wide range of climates--they are not limited to temperate areas only.

A major disadvantage with GHP's is the capital cost of the ground source heat exchanger. The size of the heat exchanger is strongly dependent on the soil conductivity, but usually about 500 feet of buried pipe per ton of GHP capacity (12,000 Btu/hr) is required (a typical 3 bedroom residence needs about 3 tons). A rough rule of thumb (the real answer depends on soil conditions, availability of experienced contractors, weather conditions, building insulation, etc.) is that GHP's cost 50 to 100% more than conventional alternatives¹. Most of this difference is due to the added cost of the ground heat exchanger. Utility rebates and substantial savings in energy costs² have led progressive residential and commercial consumers to install GHP's and most are pleased, both in terms of performance and life cycle costs. Today, approximately 35,000 GHP systems are being installed annually in the United States³. Enhanced market penetration in the future will probably require a combination of increased awareness about GHP's and reduction in capital costs

through rebates, manufacturing economies, and technical improvements.

The cost of operating GHP systems relative to alternatives varies considerably with climate, effectiveness of the heat exchanger, and local energy costs. For cooling, electricity use with GHP's is usually 20-25% less than with conventional electric air conditioning. Heating is more complex owing to the diverse set of alternatives. Relative to resistance heat (still widely used in areas with low electric costs or low heating loads), GHP's can reduce consumption by factors of 2 to 4. Relative to natural gas, fuel oil, or propane, the energy costs for heating with GHP's is about the same. This conclusion depends on the relative cost of fossil fuels to electricity, which varies regionally.

For emissions of greenhouse gases and other pollutants, the EPA¹ sees GHP's as having potential to yield significant reductions--provided their market penetration is increased. DOE has established an ambitious goal⁴ of increasing installations to 400,000 units per year by the year 2000 through marketing, R&D, and incentive programs.

Sandia National Laboratories recently established a program on GHP's designed to support the growth of the industry. The program today has three major components: support of selected demonstrations and data acquisition projects to solidify the performance claims for GHP's; an R&D component directed toward reducing costs of ground source heat exchangers; and, support of DOE's efforts to market the concept. In this paper, the progress and plans for the first two program areas will be highlighted. First, a description of the ongoing demonstration projects will be summarized. Next, the R&D activities will be presented. The specific topics covered are a vertical drilling survey, initial data from an experimental vertical ground loop heat exchanger at SNL, and results of an analytical borehole backfill study.

DEMONSTRATION PROJECTS

One of the first GHP projects SNL became involved with is the new HVAC system for Stockton State College in southern New Jersey. Their GHP system is one of the largest, closed loop installations built in this country. It supplies cooling and heating for a 360,000 square foot academic complex. There are 400 vertical closed-loop wells serving 1500 tons of roof-mounted GHP's. The wells are each about 450 feet deep and are located on a 15 foot grid under one of the college parking lots.

The roof-mounted GHP units replaced, one-for-one, natural gas/electric AC units which had been in service since the early 1970's. SNL sponsored a comprehensive electrical demand measurement program through the summer of 1993 to establish baseline data to compare with the new GHP system. The GHP hardware was put into operation in January of 1994, and measurements are planned through 1994. These measurements, combined with the baseline data, should provide an excellent basis for assessing GHP effectiveness.

SNL is also involved with the Strategic Environmental R&D Program (SERDP) through DOD with funding identified to encourage the use of GHP's on military installations. Through SERDP, GHP measurement and/or demonstration projects are underway at three military installations, and about ten others are under consideration⁵. SNL's role in the SERDP demonstrations is to provide limited seed funding to reduce the first cost and to conduct and document measurement programs. The measurement programs are generally carried out by universities, private contractors, or DOD laboratories. We expect that the SERDP will ultimately provide an excellent source of data on GHP performance of use to both the military and private sector.

RESEARCH AND DEVELOPMENT ACTIVITIES

As mentioned above, the ground heat exchanger is a major cost element for GHP systems. The configurations of the heat exchangers vary, but can be roughly classed as horizontal (installed with trenchers or backhoes) or vertical (installed with rotary drilling rigs). In residential applications, the horizontal exchangers are more popular. They usually cost less, particularly with the development of the SlinkyTM configuration by Oklahoma State University⁶. This concept buries loosely coiled pipe, rather than straight loops, and reduces the net volume of excavation needed for each installation. There are many cases, however, when vertical loops are the best option due to space limitations. They are not always more expensive than horizontal if drilling conditions are favorable and local drillers skilled in the art of ground loops are available.

SNL is currently focusing its R&D efforts on vertical installations. This is because of its experience with geothermal drilling technology and the belief that low-cost, vertical techniques are necessary to increase the penetration of GHP's.

Vertical Drilling Survey

We contracted for a survey (Huttrer⁷) of drilling and completion techniques now being used for vertical,

closed loop installations. The survey revealed that experienced loop drillers can profitably install loops for under \$5 per foot of well depth. Depending on soil conditions, the installed cost per ton ranges from \$750 to \$2000. Experience is a key factor in well costs. Water well drillers not accustomed to ground loops tend to charge much higher per foot rates, in line with their water well experience. The survey concluded that substantially lower costs are possible with a steady market to support competitive drillers with enough work to develop their own productivity improvements.

Experimental Program

To gain experience with vertical closed loop installations, SNL installed an experimental closed loop heat exchanger in Albuquerque. This was a water-filled, cased well (to facilitate installation and removal of test loops) installed in very dry soil (Figure 2). The loop was monitored with an automated data acquisition system for a constant heat input. Two separate 50 foot deep dry instrument wells were installed at roughly 3.5 and 30 ft radii from the test well, respectively. These instrument wells monitor ground temperature, so that heat diffusion from the loop may be observed. The heat transfer fluid in this loop is tap water circulated with an adjustable speed pump set at 2.2 GPM. The loop temperature is measured at four locations in the loop (hot water heater inlet and outlet, and heat exchanger inlet and outlet) using four-wire immersion type

Figure 2. Details of SNL Test Loop.

platinum resistance thermometers. Copper constantan thermocouples were used on the two 50 foot dry wells to monitor ground temperature at various depths around the heat exchanger.

We learned much from the installation of this well. The drilling was done by a local water well contractor (Albuquerque has no GHP contractors) and cost roughly \$30 per foot. This included the welded casing (a special requirement of our test) and a much larger diameter bore (9 3/4 inches) than is normally used for this application. The casing was grouted to the formation with bentonite, a commonly used backfill for vertical heat exchangers⁸. The dry soil in this area would not contain the bentonite, so the grout level would not stay at the surface. Several additional treatments of bentonite and lost circulation materials were added to limit loss of bentonite, but the loss continues. Clearly, bentonite does not work very effectively in this bore. For future installations, we will backfill with cementitious materials or other alternatives. The experience reinforced the need for research on completion methods for GHP wells. NRECA and EPRI are sponsoring such research at South Dakota State University⁹.

The thermal behavior of the loop has been measured and is summarized in Figure 3. This test consisted of applying a constant 4.8 kW heat removal rate from the heat exchanger (corresponding to 16,000 Btu/hr, or roughly 1.9 tons of GHP capacity). This test ran continuously (excepting power outages) for about 1000 hours. The loop temperature peaked at about 120°F from an initial temperature of 63°F. This, of course, is a much higher loop temperature than would be realized with a 1.9 ton GHP, because installations do not operate at a 100% duty cycle.

The squares in Figure 3 are results using Lund¹⁰ software, a commonly used vertical heat exchanger design tool. We have not yet independently measured the soil properties at our site (this is planned for this summer), but did adjust the conductivity and diffusivity values to match the measured data. Another parameter needed to apply the Lund model is R_b , the thermal resistance per unit length of bore between the loop pipes and the water-filled casing. Tables included with the Lund package recommended R_b of 0.2 K/(W/m). For our configuration we found 0.1 K/(W/m) to fit the data better. The lower thermal resistance may be due to free convection in the water. The Lund software

matches the data very well, but only after adjusting all the properties to fit.

This loop performed much better than we expected, as we thought the soil properties at the site would be more like the "light dry" soil prediction shown in Figure 3. The "light dry" soil properties are from Reference 2, which also has properties for "heavy dry" and "heavy damp" soils. (The units for the property values shown in Figure 3 are Btu/hr-ft-°F for thermal conductivity, k , and ft²/hr for thermal diffusivity, α .) This needs more investigation, as the ability to estimate local soil properties has a profound influence on loop performance. The grout which was added to the well between the casing and formation also plays a role in the performance of this loop, and it is not accounted for with the Lund predictions in Figure 3.

Our plans for this test program are to continue work with vertical polyethylene loops to investigate ways to improve predictive analysis of their performance, attempt to install some test loops at lower cost, and identify other means of completion which are more stable for the Albuquerque, New Mexico area. We also intend to do comparative testing of alternative

geometries and/or materials for ground loops which may offer improved heat transfer.

Analytical Borehole Backfill Study

Improving the thermal performance of the ground source heat exchanger is paramount to reducing the capital cost of GHP systems. The heat transfer is highly sensitive to the thermal conductivity of the medium in which the pipe is buried. During installation of the heat exchanger loop, some method of backfilling is required. Bentonite grouts are used by many drilling contractors while some loop installers just backfill with the soil removed during the drilling operation⁷. The effectiveness of the backfilling operation as well as the material used greatly affects the heat transfer and thermal performance of the ground source heat exchanger.

A parametric study of the effectiveness of using a high thermal conductivity backfill material on the ground heat exchanger performance was completed (Figure 4). For this study, the heat transfer characteristics of a single pipe heat exchanger were simulated using the P/THERMAL¹¹ Code. A one inch SCH 40

polyethylene pipe was modeled. The energy input to the heat exchanger pipe was 24 Btu/hr per foot of loop length (corresponding to 12,000 Btu/hr for a 500 foot loop). A backfill diameter of 6 inches was used. Figure 4 shows the heat transfer coefficient per unit length of pipe as a function of operating time for two different soil types and ratios of backfill material thermal conductivity to soil thermal conductivity (k_{bf}/k_{soil}) of 1, 2, and 4. It should be noted that these backfill/soil thermal conductivity ratios are representative of actual field conditions. For example, the conductivity ratio of bentonite grouts to "light dry" soil is on the order of 2 and other grouts with additives can have thermal conductivities 4 to 5 times larger than "light dry" soil⁸. Similar ratios are found with sand and clay backfills compared to some soils¹².

Figure 4 shows that the thermal performance of the heat exchanger is enhanced by approximately 15% if the backfill material is twice as conductive as the soil and at least 25% enhancement is achieved if the backfill is four times as conductive as the soil. Note the diminishing return as k_{bf}/k_{soil} increases and that the soil properties make a more substantial difference in the heat transfer effectiveness. The performance could be improved further if the radial extent of the higher conductivity backfill were increased. However, increased drilling costs for a larger diameter hole may offset any gains in thermal performance.

Future plans include modeling actual U-tube configurations (a 2-D problem) to determine if the energy transfer between the two legs of the U-tube pipe significantly changes the conclusions drawn from this 1-D study. In addition, alternative geometries will be analyzed and tested in the SNL experimental loop in the hopes of improving the thermal performance and lowering the ground loop installation costs.

CONCLUDING REMARKS

The GHP concept appears to be one of the most appealing and simple renewable energy concepts. We have attempted to initiate and develop an R&D program aimed at increasing the marketability of GHP systems with a multi-faceted approach involving demonstration projects, experiments, and modeling for enhanced performance of GHP systems. We hope the results of this endeavor will contribute toward encouraging the growth of the GHP industry.

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