PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

A NOVEL CONCEPT TO ENGINEERED GEOTHERMAL SYSTEMS

Henrik Holmberg[1], Otto, K. Sønju[2] and Erling Næss[1]

[1]Norwegian University of Science and Technology
Department of Energy and process Engineering
NO-7491, Trondheim, Norway
[2]Rock Energy AS, N-1327 Lysaker, Norway
e-mail: henrik.holmberg@ntnu.no

ABSTRACT

Geothermal energy has emerged as one of the viable options in a future clean energy based society. It poses a nearly inexhaustible resource with a worldwide potential. As pointed out in several recent publications, engineered geothermal systems (EGS) represent the future development of geothermal energy. These systems are still in the development stage while commercialization is lurching in the near future.

The common concept representing an EGS relies on engineered fractures for permeability and heat transfer area. This paper elaborates on a different and novel approach to the EGS concept, where wellbores instead of fractures are used. The system consists of a production well and an injection well interconnected by drilled wellbores. The wellbores act as a subsurface heat exchanger with a limited, but well defined heat transfer area. The result is a system that can be controlled and adapted to the specific thermal and geological structure of the site and that reduces the uncertainties regarding reservoir lifetime, thermal breakthrough, connectivity and short-circuiting. Since there is no fracturing involved, the construction of the system does not cause seismic events, and the system can, therefore, be built directly within populated areas to provide heat and power where it is needed.

The thermal performance of this type of system is characterized by an initial decline in thermal effect which reaches a semi-steady state after a few years. Thus the system has to be dimensioned for its performance at year 20 or 30 of operation. Interestingly, the performance between 30 and 50 years degrades with only 1 %, thus showing the long term sustainability of the concept. This paper presents the concept and demonstrates its performance based on geological prerequisites.

INTRODUCTION

Geothermal energy has unique features as it is one of few renewable resources that can be used for continuous base load production of clean heat and power. Thus it has a given role in a future energy system. The starting point for this article is in Norway, a country with vast hydropower resources and a cold climate, this together with a moderate geothermal gradient makes production of heat the obvious choice.

System outline

The system outline would consist of a production well and an injection well interconnected by drilled wellbores. These wellbores would thus act as a subsurface heat exchanger with a limited, but well defined heat transfer area. This creates a system that in theory can be controlled and adapted to the specific thermal and geological structure of the site. A principle sketch of the system is shown in Figure 1.

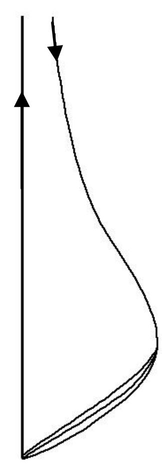

Figure 1: The system consists of an inlet and an outlet well that are connected through deviated wellbores.

The concept has previously been presented in a US-patent (2001) and was mentioned in Sanyal et al. (2005). Rock Energy AS is presently developing this concept further. The aim with this article is to elaborate on the thermal aspects of this type of concept.

The vertical extent of the system depends on the thermal structure and properties of the rock together with the designated production temperature and thermal effect. Today, accessible depths are considered in the range of 5000 m (Tester, 2006), (IGA Roadmap, 2011).

The process in which such system would extract heat is best described as mining of heat, as a heat sink will develop around the wellbores. By adopting the system to the limits of heat conduction, the process can be continuous for a significant amount of time.

This type of geothermal concept involves much more drilling than creating a heat exchanger through fracturing the rock; it would also have a restricted heat exchange area, directly linked to the amount of drilling and thus the cost. The cost of drilling is very important, and the use of modern drilling technology is essential. On the other side, the concept will directly cut away uncertainties involved with EGS regarding reservoir lifetime, thermal breakthrough, connectivity and short-circuiting (Workshop, 2007). Since there is no fracturing involved, the system would not cause seismic events and could thus be built directly within populated areas to provide heat and power where it is needed.

Heat transfer

The primary heat transport mechanism in such systems would be heat conduction within the rock and convection between the flowing water and the surface of the wellbore. Since the thermal resistance in the rock is orders of magnitude higher than the resistance between the fluid and the wellbore, it will be governing for the rate of heat transfer. Thus for such conduction based concepts it is important to have a sound estimate of the thermal properties of the rock.

Short circuiting means that the fluid takes the path with the least flow resistance. For a fractured based EGS this means that instead of spreading through the whole fractured network, the fluid will take the easiest path and thus capture less heat than it otherwise could. With wellbores constituting the heat exchanger the flow resistance can be controlled to avoid short circuiting.

Thermal breakthrough will here be defined as the point when the wellbores start to have thermal interaction. By engineering the heat exchanger with drilled pathways, the risks for thermal breakthrough can in theory be controlled and avoided.

Wellbore heat transmission

To asses such a system it is important to consider the heat transfer around the wellbore, this is commonly referred to as the wellbore heat transmission. It has been treated by authors like Ramey (1962), Horne and Shinohara (1979) and Pruess and Zhang (2005). Pruess and Zhang (2005) mentions that it can have importance as the heat transfer in the wellbore is of the same order of magnitude as a major fracture in the geothermal system. However, it is often neglected in conventional hydrothermal systems. There are two primary reasons for this, hydrothermal systems are targeted at relatively shallow depths of around 2-2.5 km and the circulation flow rates are high.

Wellbore heat transmission is a well known concept in relation to the petroleum industry where controlled wellbore temperatures during injection and production are desired. The usual assumption when calculating the heat transfer, is that the thermal resistance is in the bedrock and that the fluid and the wellbore surface are at thermal equilibrium, thus the Biot number is large. Most practical methods relate to the classical semi-analytic approach by Ramey (1962) that uses the line source from Carslaw and Jaeger (1959). The problem can as well be treated with the analytical solution for a cylindrical geometry within an infinite domain (Carslaw and Jaeger, 1959). These solutions are also frequently used for simulation of shallow ground source heat pump systems (Bernier, 2000). However, with numerical methods it is possible to study the heat transfer in more detail, (Pruess and Zhang, 2005). This also allows for variation in physical properties and simplifies for time dependent variation of heat extraction rates.

Discretization of the concept

To analyze the system one can start with neglecting the heat transfer in the injection and production wells. With sufficiently good insulation in the upper part of these wellbores this can be a viable simplification. If the wellbores in the subsurface heat exchanger are placed sufficiently far from each other to avoid thermal breakthrough within the desired operation time, and the fluid flow will be evenly distributed, the performance of one single wellbore can be representative for the whole system. This wellbore can be discretized along its axial length into sections of unit length, thereby neglecting axial conduction. Figure 2 describes the discretization of the system.

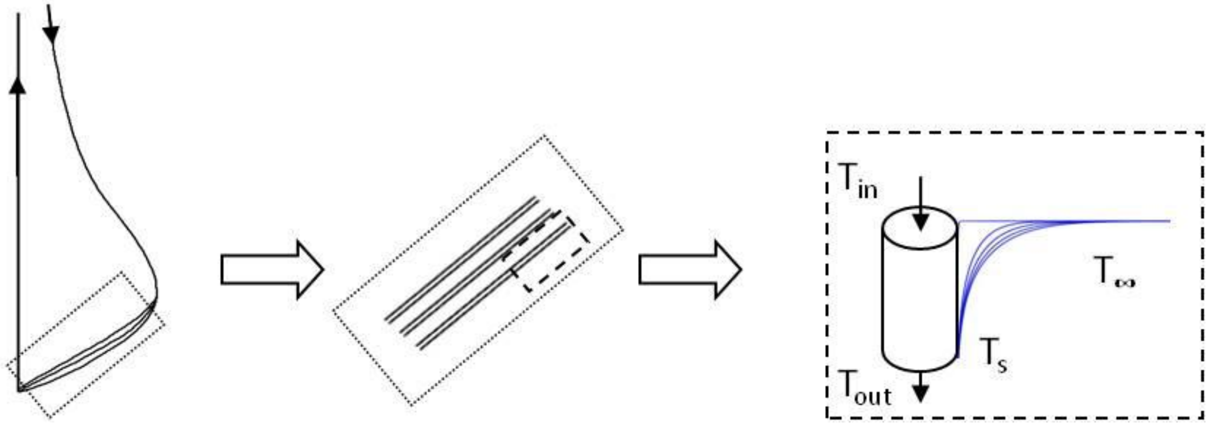

Figure 2: Discretisation of the EGS concept from full system down to unit length segment of the wellbore.

Within a section of the wellbore a heat carrier fluid will flow with turbulent conditions leading to a high heat transfer coefficient between the fluid and the wall of the segment. Depending on the structure and integrity of the rock there might be a casing between the rock and the fluid. Assuming that there is good thermal contact between the casing and the bedrock, the overall thermal resistance between the turbulent fluid and the wall can be lumped together with the resistance of the casing and the higher resistance of the bedrock. See figure 3.

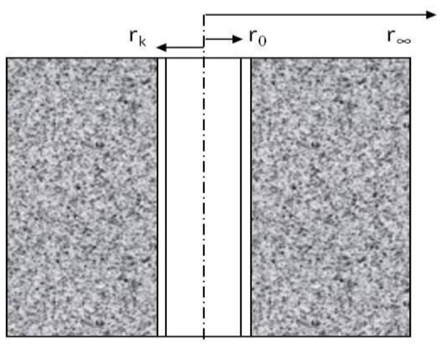

Figure 3: Cross section of wellbore segment. r_0 is the radius of the wellbore, r_k is the radius of the casing and r_∞ aims at the infinite undisturbed rock around the wellbore.

For illustration, the thermal conduction in the bedrock can be represented by an equivalent heat transfer coefficient h_∞. The thermal network may be expressed as Equation 1.1 and 1.2

$$\frac{1}{2\pi r_0 h} = \frac{1}{2\pi r_0 h_0} + \frac{\ln(r_k / r_0)}{2\pi k_c} + \frac{1}{2\pi r 2 h_\infty} \qquad (1.1)$$

$$\frac{1}{2\pi r 2 h_\infty} \approx \frac{1}{2\pi r_0 h_0} + \frac{\ln(r_k / r_0)}{2\pi k_c} \qquad (1.2)$$

h_0 is the convective heat transfer coefficient and k_c is the thermal conductivity of the casing material.

This gives a heat transfer coefficient h (W/m^2 K) between the wellbore and the surrounding bedrock which is a function of primarily the thermal diffusivity of the bedrock and time.

A heat duty per unit length (Q^*) of wellbore can be considered, this will then be dependent on the heat transfer coefficient and the temperature difference between the rock and the fluid, as follows:

$$Q^* = h\, D\, \pi\, \left(T_\infty - T_s\right) \qquad (1.3)$$

where T_∞ is the undisturbed temperature far from the wellbore, T_s is the temperature at the surface of the wellbore and D is the diameter of the wellbore.

If the temperatures T_∞ and T_s are being held as constants, the unit length heat flux will be proportional to the heat transfer coefficient, which is dependent on the properties of the rock and the heat extraction history.

<u>Numerical evaluation</u>

Numerical evaluation of the concept has been performed based on the finite-difference method with the use of Matlab. This has been done by representing the wellbores with 1-d models that are then coupled with 2-d radial models for the surrounding rock domains. This enables transient simulation with sufficiently small time-steps to study the system with hourly load variations, while still performing simulations of the full life-length of the system.

The thermal properties of the simulated rock domain are allowed to vary with temperature. The dependencies are according to the empirical equation by Sass et al. (1992) and Vosteen and Schellschmidt, (2003) for thermal conductivity (k), see Equation (1.4).

$$k(T) = \frac{k_0}{a + T\left(b - c/\ k_0\right)} \qquad (1.4)$$

The coefficients **a**, **b** and **c** have been based on Vosteen and Schellschmidt (2003) for basement rocks. For specific heat capacity the normalized empirical equation of Waples and Waples (2004) for nonporous rock has been used.

The temperature dependencies are visualized in Figure 4.

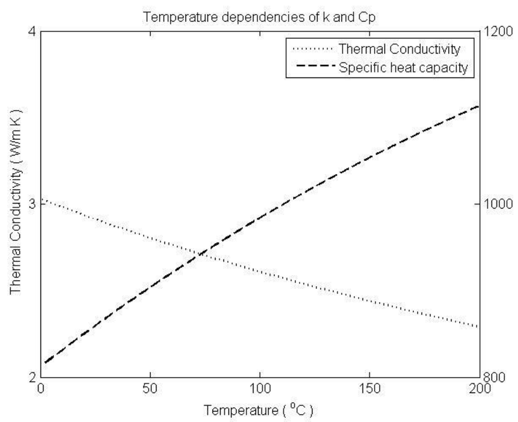

Figure 4: Temperature dependency of thermal conductivity and specific heat capacity.

Thermal conductivity is temperature dependent mostly due to the effect of phonon scattering. This causes the thermal conductivity around the wellbore to increase as energy is being extracted. The specific heat capacity increases with temperature and will thus decrease as the temperature around the wellbore decreases. This means that the heat transfer coefficient defined in Equation (1.3) is a function of the temperature field around the wellbore.

Thermal conductivity of crystalline rocks also depends on porosity. Porosity is a function of pressure, and for the considerable depth considered for the heat exchanger wellbores, the pressure should be high enough to close any intrinsic porosity in the rock. The influence of porosity has, therefore, been neglected in this paper. However, it should be mentioned that results from deep drilling projects have shown that there can be zones with increased porosity and migrating fluids even at considerable depths (Huenges et al. 1997).

The aim of the numerical model has been to further explore this type of concept beyond the limitations of simpler analytical solutions, and to exploit how the system reacts for different operating strategies. Some characteristic results will hereunder be presented.

Results are presented based on continuous heat extraction. This is sufficient to describe the main characteristics of the system. In reality the system would likely operate with a variable load. This can be achieved either by changing the mass flow rate or through bypassing the heat carrier fluid and thus changing the inlet temperature. A change in mass flow rate is directly felt by the system and thus has a direct impact on the produced energy. Bypassing causes the inlet temperature to increase, the response in change of production temperature will then be delayed with the time it takes the fluid to travel through the system. In addition, both methods cause a lagging thermal response in the bedrock.

RESULTS

It is of interest to explore the long term sustainability of this type of concept. As mentioned the process whereby heat is being extracted can be called mining of heat. Heat is being transported away from the wellbore faster than it can be replenished. This causes a rapid drop in temperature around the wellbore. The heat duty of the system will thus decline rapidly in the beginning until it reaches a semi-steady state. If the system is dimensioned based on this semi-steady extraction process it is possible to create a process which can be continuous for a significant amount of time. This can be visualized either by the change in thermal performance or the heat transfer coefficient over time. Given that the wellbores are placed with a sufficient distance in-between to avoid thermal breakthrough, the curve in Figure 5 will be representative for the thermal performance of the entire system.

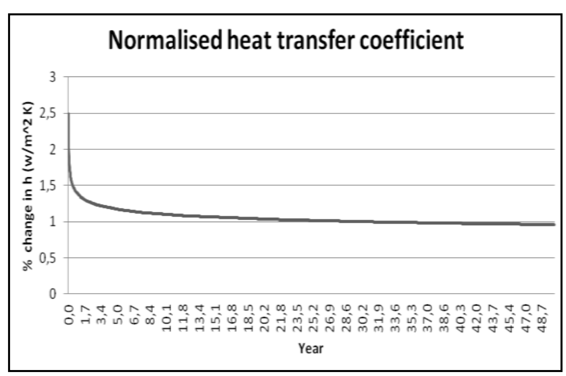

Figure 5: The graph shows the heat transfer coefficient as a function of time, the values have been normalized by the value of year 30. As can be seen the decline after year 30 is small.

The thermal properties govern how quickly heat diffuses though the rock, this is important as it determines the distance the heat diffuses during the lifetime of the system and thus the required distance between the wellbores. As mentioned, both the specific heat capacity and the thermal conductivity have strong temperature dependencies. This can be visualizes by plotting the thermal conductivity and specific heat capacity around the wellbore. See Figure 6.

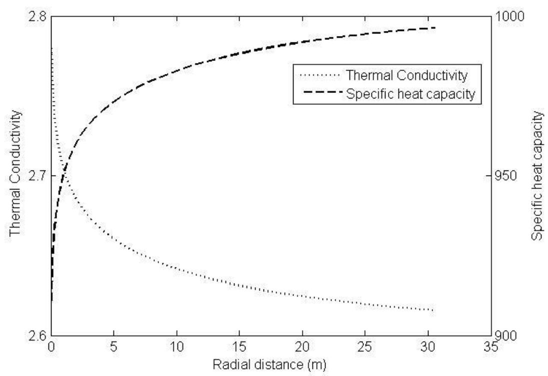

Figure 6: Thermal conductivity and specific heat capacity varies in radial distance from the wellbore due to their temperature dependencies.

As seen in Equation (1.3) the heat duty is dependent on the diameter of the wellbore, and thus on the heat transfer area. However, by decreasing the diameter of the wellbore, the thermal performance of the system is only slightly affected. This means that if possible, a smaller diameter would probably reduce the drilling costs for the system. This would then be limited by the subsequent increased pressure drop and the available drilling technology. The dependency of borehole diameter on the thermal performance can be visualized by plotting the product of the heat transfer coefficient and the surface area of the segment, as shown in Figure 7.

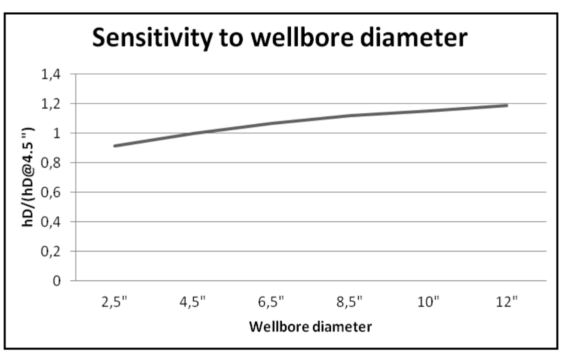

Figure 7: Normalized plot of the product between the heat transfer coefficient and the wellbore diameter for different diameters. The figure shows that the heat extraxtion only increases sligthly with increased diameter.

A typical temperature profile through the system is visualized in Figure 8. In this figure the water enters the system at 60 °C and returns at 90 °C.

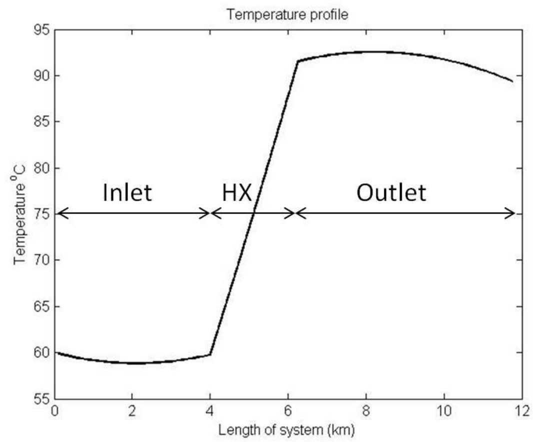

Figure 8: Typical temperature profiles through the geothermal system. This is simulated without insulation in the upper wellbores. HX refers to the heat exchanger wellbores.

And as can be seen, the temperature decreases in the inlet and outlet wellbores. Thus there are some heat losses that could be reduced by adding insulation to the wellbores. These are most prominent during the first years of operation, and are significant only for smaller systems.

<u>Sensitivity to thermal conductivity</u>

The heat transfer coefficient is strongly dependent on the thermal conductivity of the bedrock. In Figure 9 the thermal conductivity in one segment has been varied between 2 and 4 W/m K. This shows the importance of accurate thermal conductivity estimates when sizing the wellbore heat exchanger. In this case the temperature dependency of the thermal conductivity has been neglected to simplify the figure.

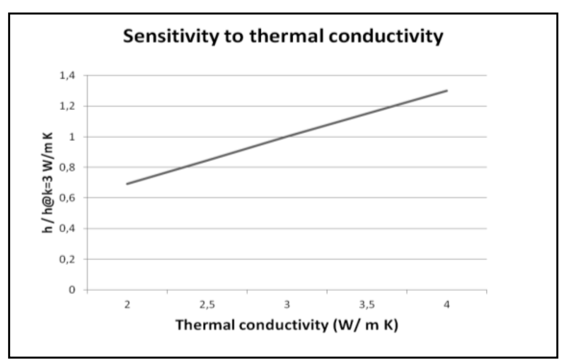

Figure 9: Normalized plot of the heat transfer coefficient and the variation with thermal conductivity of the rock.

DISCUSSION:

The aim with this paper has been to present some characteristics of a novel EGS concept based on wellbores instead of fractures. The thermal aspect of the system has been in focus. The primary features of the concept are the predictability and the long life-time.

The motive has been to provide heat at moderate temperatures for district heating, this is a limitation imposed by the geological conditions in Norway and not a characteristic for the concept. Nevertheless it affects the way the system has been analyzed and thus the results.

Thermal conductivity of the bedrock is one key-factor that has to be considered for this type of concept. There are many factors that govern the thermal conductivity of rock, of which some have been presented in this paper. Accurate dimensioning of the system requires accurate determination of in-situ thermal conductivity. There are several different empirical equations in the literature that describes the temperature dependency of thermal conductivity. The general trend is, however, the same and the difference between them have little influence on the results in this paper.

There are several factors that could affect the results. For example, it has been assumed that the rock is an impermeable medium where conduction is the sole heat transfer mechanism. Thus the impact of advection has not been considered in this paper.

To eliminate losses and improve the performance of the system it is advisable that some type of insulation is placed in the upper parts of the inlet and outlet wells. This is of course dependent on the actual operation conditions for the system.

The geometry of the system and the operating conditions govern the overall pressure drop and the energy required to circulate water in the system. In general this energy consumption amounts to less than 1 % of the thermal heat duty of the system.

Heat transfer surface is often a key factor in EGS, it should, therefore, be noted that for this type of concept the performance is not very sensitive to the diameter of the wellbore, but more related to the length of the wellbores and the temperature difference as the driving force. In Figure 7, the product of the heat transfer coefficient and the wellbore diameter increases with 43% when the surface area is increased 380 %.

CONCLUSIONS:

Some thermal perspectives of a novel EGS concept based on wellbores instead of fractures has been presented. The concept poses an alternative way of considering EGS.

The thermal properties of the rock are essential for this type of concept as it relies only on conductive heat transfer for the extraction of energy.

Predictability and simplicity are the major strengths of the concept, while increased requirement for drilling is the most likely weakness.

The long term sustainability of the concept has been demonstrated in the results. Accurate dimensioning of the system requires measurements of in-situ thermal properties. Once operative, the system can provide heat at a near constant rate for a significant time, (50 + years), with low energy requirements for circulation.

To eliminate thermal losses in the inlet and outlet wells, insulation of the upper wellbores should be considered.

The optimal diameter of the wellbores in the heat exchanger part is a function of heat extraction rate, pressure drop and available drilling technology.

REFERENCES

Bernier. M. (2000), "A Review of the Cylindrical Heat Source Method for the Design and Analysis of Vertical Ground-Coupled Heat Pump Systems". 4th International Conference on Heat Pumps in Cold Climate, Aylmer, Québec.

Carslaw. H.S., J.C. Jaeger. (1959), Conduction ofheat in solids, second ed., Oxford University press, Oxford.

Horne. R.N. and Shinohara. K. (1979), "Wellbore Heat Loss in Production and Injection Wells," *Journal of Petroleum Technology*, **31**, 116-118.

Huenges. E., J. Erzinger., J. Kück., B. Engeser., W.Kessels. (1997), "The permeable crust: Geohydraulic properties down to 9101 m depth," *Journal of Geophysical research*, **102**, 18 255-18 265

IEA (2011) "Technology Roadmap, Geothermal heat and Power," Available at http://www.iea.org/papers/2011/Geothermal_Roadmap.pdf

Pruess. K. and Y. Zhang. (2005) A Hybrid Semi-Analytical Numerical Method for Modeling Wellbore Heat Transmission, Proceedings, *30th Workshop on Geothermal Reservoir Engineering Stanford University*

Ramey. H.J. (1962), "Wellbore Heat Transmission," *SPE* **9**, 465-474.

Sass. J. H., A. Lachenbruch. and T. H. Moses. (1992), "Heat Flow From a Scientific Research Well at Cajon Pass, California, *Journal of Geophysical research*," **97**, 5017- 5030

Tester. J.W. et al. (2006). "The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century," MIT - Massachusetts Institute of Technology, Cambridge, MA. 358 p. Available at http://www1.eere.energy.gov/geothermal/future_geothermal.html.

U.S. Patent, #6,247,313B1, 19 June 2001

Vosteen. H-D. and R. Schellschmidt. (2003), "Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock", *Physics and Chemistry of the Earth* **28,** 499-509.

Waples. D.W. and J.S. Waples (2004), "A Review and Evaluation of Specific Heat Capacities of Rocks, Minerals, and Subsurface Fluids, Part 1," *Minerals and Nonporous Rocks Natural Resources Research*, Vol. **13**, No. **2**.

Workshop. (2007), Enhanced Geothermal Systems Reservoir Management and Operations Workshop, San Francisco CA, September 17, 2007, Available at http://www1.eere.energy.gov/geothermal/pdfs/reservoir_management.pdf