PROCEEDINGS, Twenty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

A HOT DRY ROCK GEOTHERMAL ENERGY CONCEPT UTILIZING SUPERCRITICAL CO_2 INSTEAD OF WATER

Donald W. Brown
Earth and Environmental Sciences Division
Los Alamos National Laboratory

ABSTRACT

A novel renewable energy concept -- heat mining using supercritical CO_2 ($SCCO_2$) for both reservoir creation and heat extraction -- is here proposed. This concept builds on the earlier, very extensive Hot Dry Rock (HDR) research and development effort conducted by Los Alamos National Laboratory at Fenton Hill, NM. This previous field testing very convincingly demonstrated the viability of the HDR concept based on the results obtained from the production testing of two separate *confined* reservoirs for almost a year each. However, using $SCCO_2$ instead of water in a closed-loop HDR system offers three significant advantages over the original Los Alamos concept:

1. The very significant wellbore density difference between the cold $SCCO_2$ in the injection well (about 0.96 g/cc) and the hot $SCCO_2$ in the production wells (about 0.39 g/cc) would provide a very large buoyant drive (i.e., thermal siphoning), markedly reducing the circulating pumping power requirements over those of a comparable water-based HDR system.
2. The inability of $SCCO_2$ to dissolve and transport mineral species from the geothermal reservoir to the surface would eliminate scaling in the surface piping, heat exchangers, and other surface equipment.
3. HDR reservoirs at temperatures in excess of 374°C (the critical temperature for water) could be developed without the problems associated with silica dissolution in water-based systems, potentially providing increased thermodynamic efficiency.

This new HDR concept would employ a binary-cycle power plant with heat exchange from the hot $SCCO_2$ to a secondary working fluid for use in a Rankine (vapor) cycle. Thermodynamic and systems analyses show that $SCCO_2$, because of its unique properties, is nearly as good as water when used for heat mining from a confined HDR reservoir. The mass heat capacity of $SCCO_2$, for the heat-transfer environment of the binary power plant, is two-fifths that of water. On the other hand, for equivalent reservoir operating conditions of surface injection pressure, reservoir flow impedance, and reservoir production pressure, the ratio of fluid density to viscosity – a measure of the reservoir flow potential -- is 1.5 times greater for $SCCO_2$ than for water, primarily due to the viscosity of $SCCO_2$ which is 40% that of water. Therefore, the rate of geothermal energy production using $SCCO_2$ would be about 60% that of water. However, on a *net* power production basis, when pumping power requirements are considered, the power production from an $SCCO_2$–HDR system wound almost equal that of a water-based HDR system.

The commercial development of this new heat-mining concept, given the ubiquitous worldwide distribution of the HDR geothermal resource, could be a significant contributor to solving two of the most pressing problems for this new century:

- The increasing need for indigenous supplies of clean energy, particularly for many of the emerging nations of Africa, Asia, and those bordering the Pacific Rim.
- Global warming resulting from ever increasing amounts of atmospheric CO_2 derived from the combustion of fossil fuels.

For the later problem, an $SCCO_2$-based HDR power plant would provide an important ancillary benefit: a means of sequestering significant amounts of CO_2 deep in the earth, when $SCCO_2$ is used for both the fracturing fluid and the heat transport fluid for deep-earth heat-mining systems. Obviously, replacing fossil fuel combustion with heat derived from HDR geothermal resources would have a greater long-term mitigating effect on global warming than CO_2 sequestration alone. To put this statement in perspective: Such an HDR power plant would have the capability of continuously sequestering, by diffusion into the rock mass surrounding the HDR reservoir, about as much CO_2 as that produced by a typical coal-fired power plant, each on a per MW-electric generation basis [24 tons of CO_2 per day per MW(e)].

INTRODUCTION

During the period from 1974 through 1995, Los Alamos National Laboratory was actively engaged in field-testing and demonstrating the Hot Dry Rock (HDR) geothermal energy concept at their Fenton Hill HDR test site in the Jemez Mountains of north-central New Mexico (Brown, 1995a). This testing ended with the very successful demonstration of sustained energy production from the deeper HDR reservoir during a series of flow tests referred to as the Long-Term Flow Test (LTFT), conducted from April 1992 through July 1995 (Brown, 1994a and 1995b). Although that program has now ended, a vast amount of information was obtained concerning the characteristics and performance of *confined* HDR reservoirs during this extended period of testing. For instance, a recent report (Brown, 1999) summarizes the data from the LTFT supporting the existence and long-term stability of a highly pressurized region of jointed rock, which is very germane to studying the deep sequestration of supercritical carbon dioxide ($SCCO_2$) in basement rock.

With the increasing awareness of global warming [as evidenced by the recent (1997) Kyoto Accords] which has been attributed by the majority of atmospheric scientists, worldwide, to be at least partially caused by the combustion of fossil fuels, the time may have arrived for a change of thinking in the US regarding increased support for renewables in general and HDR geothermal energy in particular. It is in this context that this novel new heat mining concept is proposed, which has the potential for improving the economics of HDR power generation and at the same time providing for the sequestering of significant amounts of CO_2 deep in the earth.

In the following discussion and analyses, $SCCO_2$ would be used as the heat transport fluid in the closed-cycle earth loop, with the heat contained in the produced geofluid ($SCCO_2$) being transferred to a secondary working fluid in a heat exchanger at the surface. This second fluid would then be used to drive an expansion turbine in a *binary*-cycle power generation system.

THE $SCCO_2$ -HDR CONCEPT

In this new concept for engineered geothermal reservoirs, which embodies much of the original HDR concept developed and demonstrated by Los Alamos National Laboratory, $SCCO_2$ would be used for both the fracturing fluid and the heat transport fluid for deep-earth heat-mining systems. As envisioned, a 3-well HDR system -- two production wells and one injection well -- would be employed to best access the fractured reservoir region (Brown and DuTeaux, 1997). For this preliminary study, the reservoir region is assumed to be located at a mean depth of 4 km in a region with a temperature gradient of 60°C/km. This gradient is available in many high-grade HDR resource areas in the western US, as shown in Figure 1 (Kron et al., 1991).

In this new HDR concept, as shown schematically in Figure 2, the heat contained in the hot geofluid would be transferred to a secondary working fluid in a high-pressure heat exchanger included as part of the surface power plant. This binary-cycle heat exchanger, however, would be fairly unusual because of the large fluid density change (and associated pressure effects) across the geofluid side of the heat exchanger -- a typical inlet to outlet density *increase* of over a factor of 2. The large buoyant pressure drive resulting from employing $SCCO_2$ as the heat transport fluid in the earth loop would be used to provide a surface production pressure close to the injection pressure, greatly reducing pumping power requirements once the HDR reservoir has been initially pressurized.

APPROACH/PERFORMANCE

Reservoir Creation

The engineered HDR reservoir region, probably approaching an ultimate volume of 1/2 cubic kilometer or more, would be created by hydraulically fracturing a deep region of essentially impermeable, hot, crystalline rock using $SCCO_2$ as the fracturing fluid instead of water. This would be accomplished by pumping $SCCO_2$ from the surface down a high-pressure tubing string, and injecting this fluid into a packed-off (i.e., pressure-isolated) interval of openhole wellbore for a period of several weeks or more, at a rate in the range of 20 to 40 kg/s.

Initially, as the pressure in the packed-off interval rapidly increases, one or more of the more favorably oriented natural joints intersecting the wellbore would start to open under a combination of tensile (hoop) stresses at the wellbore surface and normal opening stresses from fluid invasion into the somewhat more permeable (than the adjacent rock) hydrothermally sealed natural joints. As pumping continues, these joints would progressively open and interconnect, forming a multiply connected region of pressure-dilated joints in the rock mass surrounding the packed-off wellbore interval, thus creating the fractured HDR reservoir.

Based on over 20 years of reservoir testing at Fenton Hill, NM, this opening of an array of natural joints is in stark contrast with the originally envisioned formation of one or more large, near-vertical, penny-shaped fractures created by hydraulic fracturing (Brown, 1995a). Based on the Laboratory's extensive experience with hydraulic fracturing of deep basement rock using water, there appears to be no limitation to using $SCCO_2$ for similar operations. It should be noted that hydraulic fracturing of sedimentary formations using $SCCO_2$, as reported by Yost et al. (1994), is now routinely done to increase the productivity of petroleum reservoirs where special reservoir conditions warrant this type of stimulation to minimize formation damage from water-based fracturing fluids.

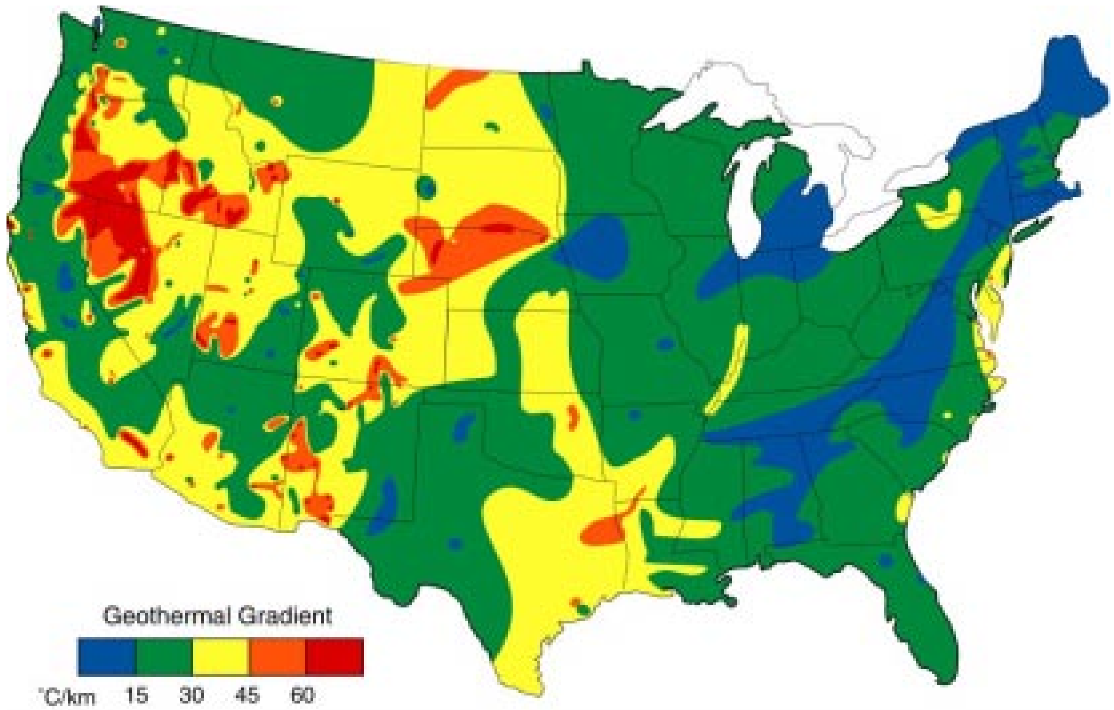

Figure 1: The Distribution of Geothermal Temperature Gradients in the "Lower 48" States.

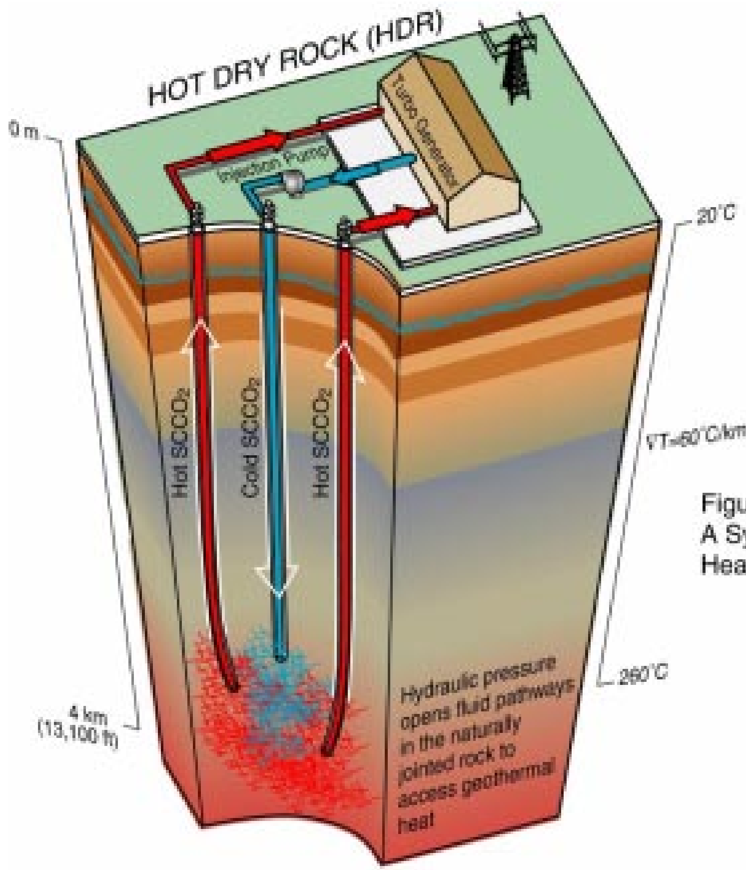

Figure 2: HDR–$SCCO_2$.
A System Engineered for Geothermal Heat Mining Using Supercritical CO_2.

Typical HDR Reservoir Conditions Assumed for this Study

Since there is not really a "typical" HDR condition yet agreed upon among the numerous workers, worldwide, involved with HDR research, the author takes the liberty of using the ***confined*** HDR reservoir conditions for the deeper Phase II reservoir at Fenton Hill, NM to represent these "typical" conditions for this first preliminary study of the $SCCO_2$-HDR concept:

Reservoir Depth = 4 km (13,120 ft)

Mean geothermal gradient = 60°C/km (ambient surface temperature of 20°C)

Reservoir rock temperature = 260°C

Closed-Loop Reservoir Circulating Conditions:

Injection pressure = 30 MPa (4350 psi)

Injection temperature = 40°C

Surface production backpressure = 30 MPa

Surface Production temperature = 250°C

Post-Hydraulic-Fracturing Fluid Composition in the Pressure-Dilated Reservoir Region

From laboratory measurements on core samples of Precambrian crystalline rock obtained from depths between 1.2 and 2.8 km at Fenton Hill, a mean in-situ rock mass porosity of 0.9×10^{-4} has been determined (Simmons and Cooper, 1977). In contrast, following reservoir creation by hydraulic fracturing and the accompanying dilation of the pressure-stimulated array of joints, the mean reservoir porosity was about 1.2×10^{-3} [24,700 m^3 of water injected into a pressure-accessible volume of 20 million m^3 (Brown et al., 1999)]. Therefore, using an analogy to the deeper Fenton Hill HDR reservoir, the fracture volume occupied by the $SCCO_2$ would be about 13 times greater then the initial microcrack pore volume in the rock mass. For this situation, the $SCCO_2$ would tend to *dissolve* almost all of the original pore fluid (essentially a brine), with the mineral constituents previously dissolved in the pore fluid being left behind as mineral precipitates. Figure 3 shows the solubility, at 250°C, of water in $SCCO_2$ and $SCCO_2$ in water as a function of pressure. For an HDR reservoir with a rock temperature of 260°C at a depth of 4 km, and with a surface injection pressure of 30 MPa, one would anticipate about a 24 mol% solubility of water in $SCCO_2$. This solubility is equivalent to a 10% solubility by weight, which would imply that *all* the previously existing pore fluid within the microcrack pore structure of the rock would end up being dissolved by the $SCCO_2$ diffusing into the rock mass.

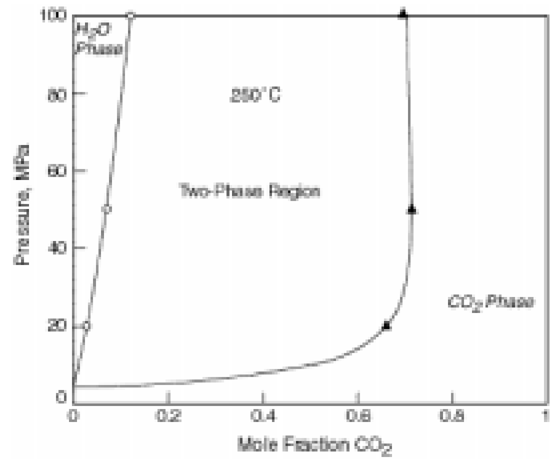

Figure 3: Phase diagram for CO_2 + H_2O at 250°C. Adapted from Shyu et al. (1997).

Reservoir Thermal Production Using $SCCO_2$ as the Working Fluid in a Closed-Loop Circulating System

This is the most unique aspect of this new HDR concept -- the use of $SCCO_2$ as both the reservoir fracturing fluid and as the heat transport fluid. As envisioned, fluid makeup with pure $SCCO_2$ (to compensate for the small amount of $SCCO_2$ slowly diffusing into the surrounding rock mass), in combination with an initial period of water separation from the produced geofluid would, within several weeks, reduce the amount of dissolved water in the circulating $SCCO_2$ to a very small amount. This "pre-conditioning" of the circulating geofluid during preliminary reservoir flow testing would probably eliminate the need for corrosion inhibition measures during subsequent power plant operation.

Thermodynamic Considerations

The potential for the $SCCO_2$-HDR concept becomes clear when one performs *overall* system studies. It is only then that the more subtle aspects of using $SCCO_2$ as a geofluid become apparent. The smaller mass heat capacity of $SCCO_2$ compared to water (0.4 vs. 1.0 in equivalent units) would at first appear to represent a considerable drawback. However, when one realizes that under realistic HDR reservoir conditions, the viscosity of $SCCO_2$ is only 40% that of water, the picture starts to change. In Table 1, the relevant fluid properties and the corresponding reservoir flow potentials for $SCCO_2$ and water are given for the anticipated reservoir conditions at 4 km.

Table 1
Comparison of Average Fluid Properties Across an HDR Reservoir at 4 km (for a surface injection pressure of 30 MPa)

Circulating Fluid:	$SCCO_2$	Water
Temperature, °C	260	260
Pressure, MPa	56.5	55.7
Density, g/cc	0.520	0.835
Viscosity, micropoise	474	1162
Normalized Flow Rate (density/viscosity)	1.10	0.72
RATIO, $SCCO_2$/Water	1.53	

As shown in Table 1 ($SCCO_2$ data obtained from Vukalovich and Altunin, 1968), for an equivalent reservoir flow impedance, surface injection pressure and reservoir outlet pressure, using $SCCO_2$ as the geofluid provides a 50% increase in the mass flow rate across the HDR reservoir as compared to water, Therefore, the overall situation for $SCCO_2$ becomes more favorable, with an anticipated thermal performance approximately 60% that of a water-based HDR system for equivalent operating conditions.

Finally, another major contributing factor to the enhanced performance of an $SCCO_2$-HDR system is the very significant buoyant drive across the reservoir, arising from the marked density contrast between the hot fluid rising in the production wells and the cold, much more dense fluid in the injection well. For an injection pressure of 30 MPa at 40°C and a surface production backpressure of 30 MPa at 250°C, the mean fluid density in the injection wellbore would be 0.96 g/cc and the corresponding mean fluid density in the production wellbores would be 0.39 g/cc, providing a density difference of about 0.57 g/cc. At a reservoir depth of 4 km, this augmented buoyant drive provided by using $SCCO_2$ instead of water as the geofluid would add an additional 22 MPa (3200 psi) to the pressure differential driving fluid across the reservoir. For the case of laminar flow which is the accepted flow regime in HDR reservoirs, this would more than double the production flow rate compared to a water-based HDR system with the same reservoir flow impedance and injection pressure, potentially providing a thermal power potential exceeding that of a water-based HDR system.

CO_2 Sequestration in the Rock Mass Beyond the Boundaries of the Fractured HDR Reservoir

Again, from experience gained from extensive field testing of the deeper HDR reservoir at Fenton Hill, the fluid loss from a 1/2 cubic kilometer pressure-stimulated reservoir volume, at a mean reservoir injection pressure of 30 MPa (4350 psi) above hydrostatic, is predicted to be about 3 kg/s for a 10-MW(e) power system, equivalent to 100,000 tons per year. Although not a very large number in absolute terms, over the predicted 20-year lifetime of a suitably engineered HDR reservoir, this diffusional loss of $SCCO_2$ into the rock mass immediately adjacent to the HDR reservoir would be very significant -- about 2 million tons of CO_2 sequestered deep in the earth for each 10-MW(e) HDR power plant. This is in addition to the 48,000 ton inventory of $SCCO_2$ circulating through the reservoir and the surface power plant for such a 10-MW(e) HDR power system.

PROBLEMS OVERCOME USING $SCCO_2$

1. Temperature Limit

As developed and extensively field tested at Los Alamos, water-based geothermal systems appear to have a geochemically determined temperature limit controlled by the approach to the critical point of water (384°C and 22 MPa). As the critical point is reached and then surpassed, the enhanced dissolution of silica followed by retrograde precipitation above 384°C appears to present a formidable obstacle to operating an HDR reservoir at higher-than-critical water temperatures. Although drilling systems are capable of reaching rock temperatures in excess of 400°C, concerns about enhanced geochemical interactions have kept Los Alamos HDR researchers from "pushing the envelope" to achieve the higher thermodynamic efficiencies that would be possible at these elevated temperatures. However, $SCCO_2$ is not a solvent for the inorganic materials found in the deep crystalline basement, and therefore the use of $SCCO_2$ would avoid the potential silica problem of supercritical water-based HDR systems. This would potentially allow for $SCCO_2$-based HDR production temperatures approaching 400°C or even higher, with the ultimate temperature probably being determined by the temperature limits of the drilling system.

2. Mineral-laden water

Although the water circulating through a high-temperature HDR system (i.e., the geofluid) is relatively benign chemically, it still contains significant amounts of dissolved minerals -- particularly silica and carbonates -- that generally precludes the geofluid from being used directly (after flashing) in an expansion turbine because of mineral precipitation. In addition, other trace materials in solution such as arsenic, fluoride, boron and hydrogen sulfide, could cause environmental problems if the geofluid were flashed at the surface, the gases vented to the atmosphere, and the resulting more concentrated geofluid not handled properly. However, when the small amount of pore fluid originally in place in the deep basement rock is dissolved in the $SCCO_2$, its dissolved mineral constituents would in turn be left behind as a small amount of precipitate within the microcrack pore structure.

This leads to an ancillary benefit at the periphery of the HDR fractured region, where the $SCCO_2$ would be slowly diffusing outward to the far field from the pressurized reservoir. In the surrounding rock mass, the pre-existing water-filled network of interconnected microcracks would be slowly flushed with $SCCO_2$, leaving behind mineral precipitates which would tend to slowly plug off the microcrack porosity and slowly seal the reservoir boundaries -- which, from the normal point of view, are almost impermeable already (with a permeability in the range of several hundredths of a microdarcy).

SUMMARY AND CONCLUSIONS

In a confined reservoir, which is one of the unique characteristics of a true man-made HDR reservoir [as contrasted with an essentially unconfined hot wet rock (HWR) reservoir or a natural hydrothermal geothermal reservoir], the chemistry and/or nature of the circulating fluid can be specified by the operator (Brown et al., 1999). For this reason, the choice of $SCCO_2$ as the working fluid is possible, and alters considerably the potential for designing unique features into such engineered geothermal systems.

In this preliminary study of the $SCCO_2$-HDR concept, it was not possible to consider all the ramifications or nuances of using a geofluid other than water as the heat transport fluid in an engineered heat-mining concept. As stated in the *Introduction* to this paper, only a single-fluid system was considered, with $SCCO_2$ used as both the heat transport fluid in the earth loop and as the surface power-plant working fluid. However, the advantages of using $SCCO_2$ in a power-producing man-made HDR geothermal system appear to be considerable.

REFERENCES

Brown, D. W. (1994a), “Summary of Recent Flow Testing of the Fenton Hill HDR Reservoir,” Proc., 19th Workshop on Geothermal Reservoir Engineering, Jan. 18-20, 1994, Stanford University, Stanford, CA pp. 113-116.

Brown, D. (1994b), “How to Achieve a Four-Fold Productivity Increase at Fenton Hill,” Geothermal Resources Council Trans., **18**, pp. 405-408.

Brown, D. (1995a), “The US Hot Dry Rock Program — 20 Years of Experience in Reservoir Testing,” Proc. World Geothermal Congress, 1995, Florence, Italy, v. 4, pp. 2607-2611.

Brown, D. (1995b), “1995 Verification Flow Testing of the HDR Reservoir at Fenton Hill, New Mexico,” Geothermal Resources Council Trans. **19**, 253-256.

Brown, D. (1999), Evidence for the Existence of a Stable, Highly Fluid-Pressurized Region of Deep, Jointed Crystalline Rock From Fenton Hill Hot Dry Rock Test Data,” Proc., 24th Workshop on Geothermal Reservoir Engineering, Jan. 25-27, 1999, Stanford University, Stanford, CA pp. 352-358.

Brown, D. and R. DuTeaux, (1997), “Three Principal Results From Recent Fenton Hill Flow Testing,” Proc., 21st Workshop on Geothermal Reservoir Engineering, Jan. 17-27, 1997, Stanford University, Stanford, CA pp. 185-190.

Brown, D., R. DuTeaux, P. Kruger, D. Swenson, and T. Yamaguchi (1999), “Fluid Circulation and Heat Extraction from Engineered Geothermal Reservoirs," *Geothermics* **28**, 553-572.

Shyu, G., N. Hanif, K. Hall and P. Eubank (1997) "Carbon dioxide--waster phase equilibria results from the Wong-Sandler combining rules," *Fluid Phase Equilibria* **130**, 73-85.

Simmons, G. and H. Cooper (1977), "DSA of the Microcracks in More GT-2 Core: Interpretation and Implications," final technical report to the Los Alamos Scientific Laboratory under Subcontract X67-69648-1, unpublished, 34 p.

Vukalovich, M.P. and V.V. Altunin, *Thermophysical Properties of Carbon Dioxide*, Translated into English under the direction of The United Kingdom Atomic Energy Authority, Collet's (Publishers) Ltd., London, 1968, 463 p.

Yost II, A.B., R.L. Mazza, and R.E. Remington II (1994), Analysis of Production Response of CO_2/Sand Fracturing: A Case Study, SPE Paper #29191, 1994 Eastern Regional Conference & Exhibition, Charlston,