21849

HEAT MINING TO EXTRACT HOT DRY ROCK (HDR) GEOTHERMAL ENERGY: TECHNICAL AND SCIENTIFIC PROGRESS

David V. Duchane
Los Alamos National Laboratory

Daniel Swenson
Kansas State University

KEY WORDS

GEOCRACK, HDR, hot dry rock, reservoir modeling, reservoir engineering, reservoir lifetime, thermal drawdown, tracers.

PROJECT BACKGROUND AND STATUS

Technology to extract energy at useful rates from the large, ubiquitous hot dry rock (HDR) resource was proposed in the early 1970's, and was disclosed in a patent issued to the Los Alamos National Laboratory in 1974 (now expired). A small HDR reservoir was constructed at Fenton Hill, NM during 1974-1978, and operated intermittently from 1978-1980 to prove the scientific feasibility of extracting energy from HDR. During 1980-1986, a larger, deeper, and hotter HDR reservoir, the Phase II reservoir, was developed at Fenton Hill. Between 1987 and 1991, a surface plant, designed to power-industry standards and capable of extended operation, was constructed and mated to the Phase II HDR reservoir. That plant was operated in a series of flow tests conducted between 1992 and 1995. Earlier Research Updates have documented the results of these tests. The USDOE ordered the decommissioning of the Fenton Hill HDR site in Fiscal Year 1996. The 1992-1995 flow-test results thus represent the end of field experimentation on HDR technology at Fenton Hill for the foreseeable future.

Over the past few years, the results of the Fenton Hill flow tests have been applied to improve the GEOCRACK reservoir model. This model is being developed by Kansas State University to more closely simulate the behavior of the reservoir at Fenton Hill during both steady-state and transient flow operations. GEOCRACK advances in 1995 included improvements in simulating reservoir flow paths by 1) the incorporation of a variable "fluid height" parameter that gives the model quasi-3D characteristics, and 2) a "far field" factor that increases the ability of the model to replicate transient fluid storage. By the end of 1995, worldwide interest in GEOCRACK was growing, both in HDR circles and in the wider hydrothermal modeling community.

PROJECT OBJECTIVES

Technical Objectives

- Work with the private sector and other interested parties to apply HDR technologies to increase the output and efficiency of hydrothermal reservoir operations.
- Work with private industry to develop niche HDR applications where and when opportunities can be identified.
- Conduct collaborative interactions with international HDR programs in Japan, Europe, and elsewhere.

Expected Outcomes

- HDR technologies should help the geothermal industry remain a competitive power source.

- Niche applications may help to document the economic factors associated with energy production from HDR and set the stage for more widespread implementation of the technologies.

- Foreign collaborations should keep the United States involved in experimental HDR work during a period when no large-scale US field operations are possible and thereby contribute to maintaining a base of HDR technical expertise in the US.

APPROACH

The Department of Energy (DOE) disclosed its intention to restructure the HDR Program at the Geothermal Resources Council Annual Meeting in October 1995. At that time, the Department also announced the cancellation of a solicitation for an industry-led HDR project to produce and market energy derived from an HDR resource. A draft decommission plan was subsequently prepared for DOE Albuquerque Operations Office (ALOO) by Los Alamos, and presented to the DOE Office of Geothermal Technologies in January 1996.

Because of the site's imminent shutdown, only a few essential field experiments were conducted at Fenton Hill in 1996. Technical development work was concentrated on improvements in reservoir modeling, and on consolidating the field data accumulated during the previous four years of field testing to provide a coherent picture of the behavior of the Fenton Hill HDR reservoir under a variety of operating scenarios.

RESEARCH RESULTS

GEOCRACK Reservoir Modeling Advances

Introduction. GEOCRACK is a fully-coupled rock-deformation/fluid-flow/thermal-drawdown model that has been developed to simulate and predict the behavior of HDR reservoirs under a variety of conditions. GEOCRACK has been continually modified to faithfully replicate the actual conditions observed during flow testing at Fenton Hill. It has also been applied to predict future reservoir performance under a number of operating scenarios.

Code Upgrades. The GEOCRACK code was modified during 1996 by incorporating algorithms that both broadened the range of application of the code and increased its operating efficiency. Some of the specific improvements are as follows:

1. Equations for density variations were derived and subsequently fluid density as a function of temperature and pressure was added to make it possible to realistically model natural circulation with GEOCRACK.

2. Tracer simulation capabilities were improved to allow modeling the behavior of thermally reactive and absorbing tracers.

3. Development of a truly 3-dimensional HDR reservoir model was begun. The 3-D model will be derived from GEOCRACK and will incorporate both its wide range of applications and its operational efficiencies.

Simulations of Reservoir Operations and Thermal Drawdown. GEOCRACK was applied to evaluate optimal flow rates for useful heat extraction from a Fenton Hill-type reservoir. This modeling produced thermal drawdown results that generally agreed with other models that have been used to predict Fenton Hill thermal performance. The modeling integrated the total thermal energy production over ten years of operation at temperatures above 150°C and 100°C, respectively, as a function of various flow rates. The results of this integration showed that production rates of 64- to 80-gpm produced more useful energy for electricity generation (assuming 150°C as the lower limit for useful energy production), than either lower or higher flow rates. Work in FY 1996 also showed the potential for applying GEOCRACK to model a reservoir that may have numerous flow paths, each with a different flow path geometry. The GEOCRACK applications reported above are discussed in much more detail in a paper presented at the 1996 Stanford Geothermal Conference (DuTeaux et al 1996).

Simulations of Reactive Tracers. A major advantage of GEOCRACK in predicting the behavior of tracers in a geothermal reservoir is the incorporation of a particle-tracking algorithm that takes into account both the overall fluid-flow rate and the time-dependent dispersion of the tracer in the fluid as it traverses the reservoir. This simulation of tracer behavior has been further enhanced by incorporating additional algorithms to simulate thermally reactive and absorbent tracers. By employing multi-component tracers repetitively, a picture of changing flow patterns or advancing cooling fronts in geothermal reservoirs could be developed. GEOCRACK could then use these data as the basis for predictive modeling that might anticipate thermal breakthrough or fluid depletion. A well-designed multi-component tracer-testing program is proving to be essential to maintaining productivity in hydrothermal reservoirs. It could be the most useful technology available for designing and evaluating the reinjection efforts that are integral to HDR operations and are rapidly becoming essential in hydrothermal field management..

Fenton Hill Reservoir Surveillance Data

Major field work on HDR in the United States was terminated as part of the DOE directive to decommission the Fenton Hill HDR Pilot Facility in October 1995. As decommission activities proceeded, however, the deep Fenton Hill reservoir was monitored periodically.

Temperature logs of the production wellbore were conducted on October 18, 1995 and January 10, 1996. The October log showed that the temperatures in that portion of the wellbore above the production zone had decreased toward the pre-existing geothermal gradient after production was terminated in July 1995. It also indicated a wash-out of the temperature profile previously observed across the production interval, with the fluid-producing fractures being somewhat less clearly delineated by temperature anomalies than during logs performed while flow testing was underway.

The January log was conducted at an ambient reservoir pressure of just over 600 psi. That log indicated a continuing recovery of the temperatures in the reservoir region of the production wellbore back toward the natural geothermal gradient; the deepest part of the profile through the reservoir zone (below 11,800 ft) exhibited warming and the shallower portion cooling. From the surface to about 9,000 ft, the wellbore temperature profile appeared to follow the previously measured geothermal gradient, indicating almost total recovery from the local heating that took place during the May-July 1995 flow test.

Logs of the injection wellbore during the early part of Fiscal Year 1996 were carried out primarily to determine the location of a breach that had been observed in the 9-5/8-in. wellbore casing. A comparison of shut-in and flowing temperature logs, conducted in October and November 1995, respectively, clearly indicated the location of the breach at about 4000 feet, and demonstrated the utility of this two-log technique for investigating wellbore problems of this type.

A subsequent log on December 14, 1995 showed about a 5°C radial-conductive recovery toward the normal geothermal gradient in the portion of the injection well extending down to 10,400 ft. From that point down to the primary injection zone at 12,000 ft, the indicated recovery was more on the order of 15-16°C, suggesting a significant convective enhancement of conductive recovery, particularly up to about a depth of 11,000 ft. This convective recovery implied both that the fractured reservoir zone extended upward at least 1,000 ft from the main injection interval, and that thermal convection was still operating within this part of the reservoir, even at the very low reservoir pressures of 600-700 psi prevailing at the time of the December log.

On May 20, 1996, an active venting process was initiated to remove water from the reservoir in preparation for plug and abandon operations. More than 500,000 gallons of water were removed from the reservoir in a series of venting operations conducted over the next several months. During each venting episode, the reservoir pressure would rapidly decline, but in the intervening periods, when the reservoir was shut-in, the pressure would increase significantly as fluid from the overpressured, and relatively impervious, region beyond the periphery of the fractured reservoir flowed back into the reservoir itself. These observed pressure increases lend additional credence to previous assertions that most of the water that was apparently "lost" during circulation through the reservoir was in reality simply stored at high pressure in the microcrack fabric of the essentially impervious rock beyond the boundaries of the reservoir proper.

By the close of Fiscal Year 1996, the pressure on the large Fenton Hill HDR reservoir was holding steady at about 302 psi. Early in Fiscal Year 1997, the system was vented to zero pressure, and operations to plug and abandon the injection wellbore were completed. The production wellbore was held open by the Laboratory for use in a variety of future tool development and other field experiments.

FUTURE PLANS

GEOCRACK Model Development

Modeling work will focus on both increasing the applicability and use of GEOCRACK for hydrothermal reservoirs and continuing the development of GEOCRACK3D. For the hydrothermal industry, GEOCRACK has application in designing re-injection strategies, understanding tracer data, and predicting the long-term effect of reservoir cool-down on flow characteristics of the reservoir. Specific developments of GEOCRACK will include: 1) the addition of porous flow in the rock blocks, 2) ease-of-use improvements (note that GEOCRACK is already fully interactive and graphical), and 3) the addition of interactive help functions. To broaden the use of GEOCRACK, training sessions will be offered at an appropriate international geothermal venue.

HDR Technology Development

The HDR Program will pursue a three-pronged effort involving transfer of existing HDR technology to the private sector, exploring niche opportunities for HDR implementation, and collaborating in international HDR projects. Technology transfer will entail 1) formulating joint projects to apply HDR technology in non-HDR hydrothermal situations, and 2) outreach events directed toward providing specific techniques and processes to the wider hydrothermal and general private-sector community. Niche HDR opportunities may exist in selected domestic and overseas markets, as part of co-generation schemes, or in other unique situations. All of these will be vigorously pursued. Finally, interactions with the established HDR programs in Japan and Europe will be continued.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Interest in GEOCRACK Modeling Work

Organization	Type and Extent of Interest
Energy and Geoscience Institute, Univ. of Utah	Tracer simulations
BGI, Consultants, USA	Reservoir simulation
Stanford University experiments	Analysis of flow in rock joint
Seoul National University Facility, Korea	Analysis of nuclear waste storage
Geoscience Research Institute flow	Modeling of glacier movement water
INGEOMINAS, Columbia	HDR simulation
CRIEPI, Japan	--------------
CSM Associates, UK	Reservoir simulation

This year GEOCRACK has been adapted for use on both computer workstations and PC's running Windows 95 or NT. The program can be downloaded from the web at site http:/www.engg.ksu.edu //~geocrack. Our observations indicate that the GEOCRACK web site is being accessed on a daily basis.

REFERENCES

Duchane, D.V., 1996. Heat Mining to Extract Hot Dry Rock (HDR) Geothermal Energy: Technical and Scientific Progress. Federal Geothermal Research Program Update Fiscal Year 1995, p 4-215 to 4-231.

Duchane, D. V., 1995. Heat Mining to Extract Hot Dry Rock (HDR) Geothermal Energy: Technical and Scientific Progress, Federal Geothermal Research Program Update Fiscal Year 1994, p 4-197 to 4-204.

DuTeaux, R., Swenson D., and Hardeman, B., 1996. Insight from Modeling Discrete Fractures with GEOCRACK: a Geothermal Reservoir Model, Proceedings of Twenty-First Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, p 287-293

DuTeaux, R., Swenson, D., and Hardeman, B., 1996. Modeling the Use of Reactive Tracers to Predict Changes in Surface Area and Thermal Breakthrough in HDR Reservoirs, Proceedings of the 3rd International HDR Forum, Santa Fe, NM. (Proceedings available from J. Benson, MS-D442, Los Alamos National Laboratory, Los Alamos, NM.)

DuTeaux R., and Callahan, T. J., 1996. Comparing Reactive and Non-Reactive Tracers to Measure Changes in Liquid-Dominated, Fractured Geothermal Reservoirs, Geothermal Resources Council Transactions, Vol. 20, p 447-451.

Swenson, D., DuTeaux R., and Sprecker T., 1995. Modeling Flow in a Jointed Geothermal Reservoir, Proceedings of the World Geothermal Congress 1995, p 2553-2559.

LIST OF CONTACTS FOR RESERVOIR ENGINEERING

Colleen A. Barton
Department of Geophysics
Stanford University
Stanford, CA 94305
Tel: (415) 723-9831
Fax: (415) 725-7344

Pascale Benezeth
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6110
Tel: (423) 574-4960

Dick Benoit
Oxbow Geothermal Corp.
5250 S. Virginia Street, Suite 304
Reno, NV 89502
Tel: (702) 825-4345
Fax: (702) 825-2838

Greg N. Boitnott
New England Research Inc.
76 Olcott Drive
White River Junction, VT, 05001
Tel: (802) 296-2401
Fax: (802) 296-8333
boitnott@ner.com

Peggy Brookshier
U.S. Department of Energy
Idaho Operations Office
785 DOE Place, MS 1220
Idaho Falls, ID 83401-1563
Tel: (208) 526-1403
Fax: (208) 526-5964

David R. Cole
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O.Box 2008, MS 6110
Oak Ridge, TN 37831-6110
Tel: (423) 574-5473
Fax: (423) 574-4961

Dave Duchane
Los Alamos National Laboratory
P.O. Box 1663
MS D443
Los Alamos, NM 87545
Tel: (505) 667-4318
Fax: (505) 667-8487

David D. Faulder
Idaho National Engineering Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3830
Tel: (208) 526-0674
Fax: (208) 526-0969
ddf@inel.gov

Stefan Finsterle
E.O. Lawrence Berkeley National Laboratory
Earth Sciences Division, B90-1116
Berkeley CA 94720
Tel: (510) 486-5205
Fax: (510) 486-5686
safinsterle@lbl.gov

Miroslaw S. Gruszkiewicz
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4500S, MS-6110
Oak Ridge, TN 37831-6110
Tel: (423) 574-4965
Fax: (423) 574-4961

Stephen Hickman
U.S. Geological Survey
345 Middlefield Rd., MS 977
Menlo Park, CA 94025
Tel: (415) 329-4807
Fax: (415) 329-5163

Juske Horita
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O.Box 2008, MS 6110
Oak Ridge, TN 37831-6110
Tel: (423) 576-2750
Fax: (423) 574-4961

Roland N. Horne
Stanford Geothermal Program
Dept of Petroleum Engineering
Green Earth Science Bldg, Rm. 65
Stanford, CA 94305-2220
Tel: (415) 723-9595
Fax: (415) 725-2099
horne@pangea.stanford.edu

Jeffrey B. Hulen
EGI/University of Utah
423 Wakara Way
Salt Lake City, UT 84108
Tel: (801) 581-8497
Fax: (801) 585-3540
e-mail: jhulen@egi.utah.edu

Ann Kirkpatrick
E.O. Lawrence Berkeley National Laboratory
Earth Sciences Division, B90-1116
Berkeley CA 94720
Tel: (510) 486-6985
Fax: (510) 486-5686
boulder@ccs.lbl.gov

Marcelo J. Lippmann
E.O. Lawrence Berkeley National Laboratory
Earth Sciences Division, B90-1116
Berkeley, CA 94720
Tel: (510) 486-5035
Fax: (510) 486-5686
mjlippmann@lbl.gov

Susan J. Lutz
Energy & Geoscience Institute
University of Utah
423 Wakara Way, Suite 300
Salt Lake City, UT 84108
Tel: (801) 585-9688
Fax: (801) 585-3540

Ernie L. Majer
E.O. Lawrence Berkeley National Laboratory
Earth Sciences Division, B90-1116
Berkeley CA 94720
Tel: (510) 486-6709
Fax: (510) 486-5686
elmajer@lbl.gov

Robert E. Mesmer
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O.Box 2008, MS 6110
Oak Ridge, TN 37831-6110
Tel: (423) 574-4958
Fax: (423) 574-4961

Nancy Møller
U.C. San Diego (Chemistry Dept.)
La Jolla, CA 92093
Tel: (619) 534-6374/3286
Fax: (619) 534-7244

Joseph N. Moore
Energy & Geoscience Institute
University of Utah
423 Wakara Way, Suite 300
Salt Lake City, UT 84108
Tel: (801) 585-6931
Fax: (801) 585-3540

Roger Morin
U.S. Geological Survey
Box 25046
Denver Federal Center
Denver, CO 80225
Tel: (303) 236-5915
Fax: (303) 236-5959

Gregory D. Nash
Energy and Geoscience Institute
University of Utah
423 Wakara Way, Suite 300
Salt Lake city, UT 84108
Tel: (801) 585-3889
Fax: (801) 585- 3540
nash@egi.utah.edu

Dennis L. Nielson
Energy & Geoscience Institute
University of Utah
423 Wakara Way, Suite 300
Salt Lake City, UT 84108
Tel: (801) 585-6855
Fax: (801) 585-3540

Curtis Oldenburg
E.O. Lawrence Berkeley National Laboratory
Earth Sciences Division, B90-1116
Berkeley CA 94720
Tel: (510) 486-7419
Fax: (510) 486-5686
cmoldenburg@lbl.gov

Donald A. Palmer
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4500S, MS-6110
Oak Ridge, TN 37831-6110
Tel: (423) 576-5109
Fax: (423) 574-4961

Peter Persoff
E.O. Lawrence Berkeley National Laboratory
Earth Sciences Division, B90-1116
Berkeley, CA 94720
Tel: (510) 486-5931
Fax: (510) 486-6057
e-mail: pepersoff@lbl.gov

John W. Pritchett
Maxwell Technologies, Federal Division
8888 Balboa Avenue
San Diego, CA 92123-1506
Tel: (619) 576-7760
Fax: (619) 576-7710
john@maxwell.com

Karsten Pruess
E.O. Lawrence Berkeley National Laboratory
Earth Sciences Division, B90-1116
Berkeley CA 94720
Tel: (510) 486-6732
Fax: (510) 486-5686
k_pruess@lbl.gov

Marshall Reed
Office of Geothermal Technologies EE-12
1000 Independence Ave., SW
Washington, DC 20585
Tel: (202)586-8076
Fax: (202)586-8185
marshall.reed@doe.hq.gov

Joel L. Renner
Idaho National Engineering Lab
PO Box 1625
Idaho Falls, ID 83415-3830
Tel: (208) 526-9824
Fax: (208) 526-0969
rennerjl@inel.gov

Ted De Rocher
Nevada Bureau of Mines and Geology, MS 178
University of Nevada, Reno
Reno, Nevada 89557-0088
Tel: (702) 849-1299
Fax: (702) 849-1328
email: Tderocher@aol.com

Dan Sanchez
Energy Projects Manager
Energy Technologies Division
U.S. Department of Energy
P.O. Box 5400
Albuquerque, NM 87185
Tel: (505) 845-4417
Fax: (505) 845-4430

John Sass
U.S. Geological Survey
2255 North Gemini Drive
Flagstaff, AZ 86001
Tel: (520) 556-7226
Fax: (520) 556-7169

Cengiz Satik
Stanford Geothermal Program
Dept. of Petroleum Engineering
Stanford, CA 94305
Tel: (415) 723-5377
Fax: (415) 725-2099
cengiz@pangea.stanford.edu

Richard A. Schweickert
Department of Geological Sciences
University of Nevada, Reno
Reno, NV 89557
Tel: (702) 784-6901
Fax: (702)784-1833
richschw@unr.edu

Lisa Shevenell
Nevada Bureau of Mines and Geology
MS 178
University of Nevada, Reno
Reno, Nevada 89557-0088
Tel: (702) 784-1779
Fax: (702) 784-1709
email: lisa@geyser.nbmg.unr.edu

G. Michael Shook
Idaho National Engineering Lab
PO Box 1625
Idaho Falls, ID 83415-2107
Tel: (208) 526-6945
Fax: (208) 526-9822
ook@inel.gov

Ardyth M. Simmons
Earth Sciences Division, B90-1116
E.O. Lawrence Berkeley National Laboratory
Berkeley, CA 94720
Tel: (510) 486-7106
Fax: (510) 486-6057
ardyth_simmons@lbl.gov

J. Michael Simonson
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4500S, MS-6110
Oak Ridge, TN 37831-6110
Tel: (423) 574-4962
Fax: (423) 574-4961

Daniel Swenson
Department of Mechanical Engineering
Durland Hall
Manhattan, KS 66506-5105
Tel: (913) 532-2320
Fax: (913) 532-7057

Alfred H. Truesdell
700 Hermosa Way
Menlo Park, CA 94025
Tel: (415) 322-6135
Fax: (415) 324-4009
ahtruesd@best.com

John Weare
U.C. San Diego (Chemistry Dept.)
La Jolla, CA 92093
Tel: (619) 534-6374/3286
Fax: (619) 534-7244

David J. Wesolowski
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O.Box 2008, MS 6110
Oak Ridge, TN 37831-6110
Tel: (423) 574-6093
Fax: (423) 574-4961

Colin F. Williams
U.S. Geological Survey
345 Middlefield Road, MS 977
Menlo Park, CA 94025
Tel: (415) 329-4881
Fax: (415) 329-4876
e-mail:colin@hq.wr.usgs.gov

Mark Zoback
Department of Geophysics
Stanford University
Stanford, CA 94305
Tel: (415) 725-9295
Fax: (415) 725-7344