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Geothermal Technology Publications and Related Reports: A Bibliography, January through December 1982

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Sandra R. Hudson, Editor

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GEO THERMAL TECHNOLOGY PUBLICATIONS AND RELATED REPORTS:

A BIBLIOGRAPHY

January through December 1982

Sandra R. Hudson, Editor
Geo Energy Technology Department II - 9740
Sandia National Laboratories
Albuquerque, New Mexico 87185

Abstract

Sandia National Laboratories has done significant research and development for the U.S. Department of Energy to understand and utilize geothermal resources. Results of the work from January 1977 through December 1981 were summarized in reports SAND81-0662 and SAND82-0993. This bibliography extends the past listings to work reported in the 1982 calendar year. Titles, authors and abstracts of papers are assembled into areas of Geothermal Technology and Magma with cross references listed by author.

The reported research was done by personnel at Sandia or at universities or industry under contract to Sandia. The major support of this work was provided by the Department of Energy Division of Geothermal Energy and the Office of Basic Energy Sciences.

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CONTENTS

	<u>Page</u>
I. Geothermal Technology.....	1
A. Rock Penetration Mechanics.....	3
B. Fluid Technology.....	7
C. Borehole Mechanics.....	13
D. Diagnostic Technology.....	15
E. Systems Analysis/Program Summaries.....	19
II. Magma Energy.....	23
A. Source Location and Definition.....	25
B. Magma Characterization.....	27
C. Energy Extraction.....	31
D. Project Reviews/Summaries.....	33
III. Author Listing.....	37
IV. Chronological Sandia Publication Listing.....	43

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For those reports which are not official Sandia reports (i.e., those with SAND numbers which are listed in Section IV), you should request copies of those from your library or by writing and requesting from the appropriate periodical or journal.

Several of the publications are available in the Geothermal Resources Council Transactions. The reference for those transactions is listed below:

Geothermal Energy: Turn on the Power!
Transactions, Volume VI, 1982 Annual Meeting
October 11-14, 1982, San Diego, California

You may request the above transactions from the following address:

Geothermal Resources Council
P. O. Box 98
Davis, California 95617

For those publications published as Proceedings of the Society of Petroleum Engineers meetings, you should write the following address:

Society of Petroleum Engineers
6200 North Central Expressway
Dallas, Texas 75206

I. GEOTHERMAL TECHNOLOGY

Introduction

The U. S. Department of Energy-sponsored program in geothermal drilling and completion research and development is managed by Sandia National Laboratories. The program objective is to conduct long-range R&D aimed at developing advanced geothermal drilling and completion systems to expand resource utilization. The technical program is organized into four broad categories: 1) Rock Penetration Mechanics, 2) Fluid Technology, 3) Borehole Mechanics, and 4) Diagnostics Technology. In addition to these R&D activities, considerable effort is made to insure that the program is properly focused and emphasizes the most important factors. This effort is broadly classified as systems analysis.

Research in Rock Penetration Mechanics is directed toward a basic description of rock penetration by advanced drilling systems. Ongoing research projects include: studies of the behavior of polycrystalline diamond compact (PDC) cutters in relation to rock fracture and wear mechanisms, improved carbide materials, cavitating jets, and percussion drilling.

The general goal of the Fluid Technology research is to develop drilling fluids specifically tailored to solve the problems encountered in geothermal drilling. The projects include the study of properties of aqueous foams which could be used as drilling fluids and the temperature and chemical effects on drilling clays. Also included are studies aimed at improving the cleaning of the hole and the removal of debris.

The R&D in Borehole Mechanics addresses the problems of lost circulation and lining and cementing the well, as well as problems of production maintenance such as perforating and scale removal. An unique high temperature lost circulation-cementing test facility is under construction which will provide data on advanced materials and techniques for controlling lost circulation and cementing casing.

Diagnostics Technology research is aimed at developing high temperature capabilities for well-logging equipment and instrumentation. This program element also includes research into areas aimed at increasing the capability to measure and evaluate downhole conditions. The tools and techniques developed as a part of this effort are basic support devices for the other program elements, yielding definition of the downhole environment for better system definition.

The Systems Analysis section lists publication of generic interest which apply to the program planning and program management tasks.

This entire section lists specific reports and technical papers which have been published in support of the Geothermal Technology Development Program. This effort supports one of the important program aspects, namely, technology transfer to private industry.

A. Rock Penetration Mechanics

DEVELOPMENT OF MODIFICATIONS FOR COFLEXIP FLEXIBLE DRILLING PIPE FOR HIGH TEMPERATURE AND PRESSURE GEOTHERMAL SERVICE-FINAL REPORT, SAND82-7203, G. J. Friese, L'Garde, under contract to Sandia National Laboratories.

Coflexip (France) flexible drilling pipe can provide economies in drilling geothermal wells. However, the current liner materials cannot take the high temperatures (approximately 250°C) and pressures (approximately 69 MPa). Development was undertaken to replace the liner with higher temperature materials and thus increase the temperature capability of the flexible pipe. DuPont Teflon PFA 350, L'Garde EPDM Y267, and L'Garde AFLAS 291 were considered but they all require backing by a closely woven stainless steel fabric to prevent extrusion. A graphite-reinforced EPDM elastomer was developed which has the potential of meeting the pressure-temperature requirements without the metal fabric reinforcement.

PETROGRAPHIC OBSERVATIONS AND MODEL PREDICTIONS FOR FRACTURE OF ROCK DURING DRAG-BIT CUTTING, J. T. Finger, D. H. Zeuch, D. V. Swenson, Sandia National Laboratories, AGU Fall Meeting, December 7-15, 1982, San Francisco, California.

As part of a program to develop new technology for the reduction of well-drilling costs, we have conducted a series of single-cutter drag-bit tests on specimens of Tennessee Marble and Westerly granite. The objective of these experiments is to obtain observational data on subsurface fracture development and chip formation that may be compared with predictions made by a two-dimensional finite element code designed to model the cutting process. Tests on the marble and granite specimens were performed at a fixed bit velocity of 3.8 cm sec⁻¹ and depths of cut of 0.254, 0.127, or 0.064 cm. The samples were subsequently impregnated with various dye penetrants, sectioned and examined using optical microscopy. The extent of subsurface damage clearly varies directly with the depth of cut. However, the fracture patterns and geometries are similar for both rock types and all depths of cut, indicating that a similar fracture mechanism operates in all of the tests. Fractures consistently dip in the direction of tool displacement, at angles ranging from very shallow to approximately 50°. There is no displacement across these fractures, indicating that they are tensile cracks. The finite element model includes tensile crack formation and, in compression, either plastic deformation or the formation of shear cracks. Results show a good qualitative agreement with the fracture patterns and inferred fracture mechanisms for the laboratory tests.

AN ASSESSMENT OF DIRECTIONAL DRILLING FOR FOSSIL ENERGY RESOURCES, SAND81-1848, Alan L. McFall, Sandia National Laboratories.

This report discusses directional drilling techniques and procedures that can be used to access fossil energy resources. Unconventional resources such as tar sands, oil shale, and tight gas formations are specifically examined. Performance requirements, current practice, a description of drilling hardware, and a discussion of key developmental needs are presented.

DIFFUSION BONDING OF STRATAPAX FOR DRILL BITS, SAND82-2309, John T. Finger and John N. Middleton, Sandia National Laboratories.

A process has been developed for the diffusion bonding of General Electric's Stratapax^R drill blanks to support studs for cutter assemblies in drill bits. This report describes the diffusion bonding process and provides bond strength test data for a variety of materials. The extensive process details, provided in the Appendices, should be sufficient to enable others to successfully build diffusion-bonded drill bit cutter assemblies.

SUBSURFACE DAMAGE DEVELOPMENT IN ROCK DURING DRAG-BIT CUTTING: OBSERVATIONS AND MODEL PREDICTIONS, SAND82-2505C, J. T. Finger, D. H. Zeuch, D. V. Swenson, Proceedings, 24th U. S. Symposium on Rock Mechanics, June 20-23, 1983, Department of Geosciences, Texas A&M College, College Station, Texas.

It has been recognized for some time now that detailed understanding of the tool-rock interaction, and the mechanism(s) of rock fracture and chip formation will be important in efforts to improve drilling technology. With specific reference to drag-bit cutting, there have been several attempts to investigate and/or model the penetration and chip formation processes (e.g., Gray, et al., 1962; Sikarskie and Altiero, 1973; Wang and Lehnoff, 1976; Hood, 1977). No effort has been expended, however, in the investigation of the damage introduced into rock during drag-bit cutting. The information gained in such an investigation, however would have several applications. First, it would shed some light on the extent to which single-cutter experiments on "intact" rock are likely to be relevant to an understanding of the actual processes involved in rock cutting in the field. Second, information regarding damage introduced into rock during drilling should be useful in determining the placement of cutters in the tool so as to optimize the interaction of fractures produced by adjacent cutters (indexing). Third, we will show that analysis of fractures produced during experimental drag-bit cutting may be useful in

cross-checking the validity of a finite element code designed to model the rock-cutter interaction and the chip-formation process.

INVESTIGATION OF THE POTENTIAL FOR USING ELECTROCHEMICAL TECHNOLOGY TO REDUCE DRILL BIT WEAR, Thomas E. Hinkebein, David A. Glowka, Sandia National Laboratories, SAND82-0896.

Recent work has shown that an important drill bit wear mechanism in aqueous environments is electrochemical in nature. The synergistic effects of corrosion and abrasion are responsible for a large percentage of bit wear in laboratory studies. It has been shown that measured wear rates can be reduced by factors of two to five with the application of a voltage potential which opposes and exceeds the galvanic potential generated by the corrosion cells existing downhole. The present study investigates the potential for applying this technique in the downhole environment. The results demonstrate that a downhole generator sub powered by drilling fluid is a possible electrical power source. Graphite is chosen as the optimal non-sacrificial anode material for this application. Steel is also shown to be a possible anode material, but the anode would be sacrificial in this case, requiring periodic replacement. The electrical power required to achieve the desired effect for a 4-1/2 inch drill bit is determined to be on the order of one milliwatt. Additionally, up to 250 feet of 4 inch drill pipe could be protected from corrosion with power levels on the order of 150 milliwatts. These relatively low power levels suggest that dry cell batteries could alternatively be employed as the power source; however, the temperature limitations of commercially-available batteries would have to be overcome for geothermal applications.

B. Fluid Technology

ADVANCED WELLBORE THERMAL SIMULATOR GEOTEMP2 RESEARCH REPORT, Robert F. Mitchell, EnerTech, under contract to Sandia National Laboratories, SAND82-7003, Volume 2 and Appendix.

This report describes the development of the GEOTEMP2 wellbore thermal simulator. The major technical features include a general purpose air and mist drilling simulator and a two-phase steam flow simulator that can model either injection or production.

An improved method for calculating downhole temperatures, pressures, fluid densities and velocities during air drilling has been developed. Improvements on previous methods include: 1) A fully transient thermal analysis of the wellbore and formation is used to determine the flowing temperatures. 2) The effects of flow acceleration are included explicitly in the calculation. 3) The slip velocity between the gas and the cuttings is determined by the use of a separate momentum equation for the cuttings. 4) The possibility of critical flow in the wellbore is tested for and appropriate changes in the volume flow rate and standpipe pressure are made automatically. 5) The standpipe and flowing pressures are predicted. 6) The analysis is conservative. The effect of the cuttings on the wellbore flow will tend to overpredict the required volume flow rates. In this report, the basic equations of fluid flow for a gas with cuttings and mist are presented along with a numerical method for their solution. Several applications of this calculational method are given, showing the effect of flow rate and standpipe pressure in typical air and mist drilling situations.

FRictional HEATING AND CONVECTIVE COOLING OF POLYCRYSTALLINE DIAMOND DRAG TOOLS DURING ROCK CUTTING, D. A. Glowka, A. Ortega, Sandia National Laboratories, SAND82-0675C, Proceedings, 57th Annual Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, September 26-29, 1982, New Orleans, Louisiana.

A numerical-analytical model is developed to predict temperatures in stud-mounted polycrystalline diamond compact (PDC) drag tools during rock cutting. Experimental measurements of the convective heat transfer coefficient for PDC cutters are used in the model to predict temperatures under typical drilling conditions with fluid flow. The analysis compares favorably with measurements of frictional temperatures in controlled cutting tests on Tennessee marble. It is shown that mean cutter wearflat temperatures can be maintained below the critical value of 750°C only under conditions of low friction at the cutter/rock interface. This is true, regardless of the level

of convective cooling. In fact, a cooling limit is established above which increases in convective cooling do not further reduce cutter temperatures. The ability of liquid drilling fluids to reduce interface friction is thus shown to be far more important in preventing excessive temperatures than their ability to provide cutter cooling. Due to the relatively high interface friction developed under typical air drilling conditions, it is doubtful that temperatures can be kept subcritical at high rotary speeds in some formations when air is employed as the drilling fluid, regardless of the level of cooling achieved.

INERT GAS DRILLING IN HOT, UNDERPRESSURED FORMATIONS, B. C. Caskey, Sandia National Laboratories, SAND82-0498C, Proceedings, 57th Annual Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, September 26-29, 1982, New Orleans, Louisiana.

Oxygen corrosion of drill pipe is a serious problem when a low-density drilling fluid (air or mist) is used in hot formations, such as in geothermal resource development. This paper describes 1) the corrosion process and the effect of important variables; 2) the results of a field test which compared air-water and nitrogen/water corrosion while drilling; and 3) the design of a full-scale, portable diesel exhaust gas purifier which will supply a noncorrosive gas for drilling.

The paper concludes that, for drilling in areas that exhibit high drill pipe corrosion, the use of a purifier would extend drill pipe life from a few months to years and that the cost of operating the purifier can be less than adding corrosion control chemicals. The purifier uses diesel exhaust from rig engines, removes any remaining oxygen and nitrous oxides through catalytic conversion, scrubs the carbon dioxide, and finally, removes the water before routing the purified gas to compressors.

OPTIMIZATION OF BIT HYDRAULIC CONFIGURATIONS, D. A. Glowka, Sandia National Laboratories, SPE 10240, Proceedings, 56th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, San Antonio, Texas, October 5-7, 1981.

Measurements of flow field characteristics across the face of a stud-mounted PDC bit have been obtained in a new test facility which simulates downhole flow fields. This facility and the measurement techniques employed to obtain the data are described. Flow tracer tracking and cutter heat transfer coefficient measurements are shown to be valuable in determining flow field characteristics, whereas the utility of the dye injection

system tested is low. Three hydraulic configurations for the bit have been tested to determine the effects of nozzle location on bottomhole cross-flow velocities and cutter cooling rates. The configuration which provides higher velocities and cooling rates is determined to be the one which employs smaller nozzles located near the center of the bit.

DESIGN OF A DIESEL EXHAUST PURIFICATION SYSTEM FOR INERT GAS DRILLING, SAND82-1404C, B. C. Caskey, Sandia National Laboratories, Proceedings, Geothermal Resources Council 1982 Annual Meeting, October 11-14, 1982, San Diego, California.

To combat the serious oxygen corrosion of drill pipe when a low density drilling fluid (air or mist) is used in geothermal drilling, a system has been designed that produces an inert gas (essentially nitrogen) to be substituted for air. The system fits on three flatbed trailers, is roadable and produces 2000 scfm of gas. The projected cost for gas is slightly less than \$2.00 per thousand standard cubic feet. Detailed design information is available from Foster-Miller Associates, Inc., in Waltham, Massachusetts.

CLAY-BASED GEOTHERMAL DRILLING FLUIDS, SAND82-7037, N. Guven, et al., Texas Tech University, under contract to Sandia National Laboratories.

The rheological properties of fluids based on fibrous clays such as sepiolite and attapulgite have been systematically examined under conditions similar to those of geothermal wells, i.e., at elevated temperatures and pressures in environments with concentrated brines. Attapulgite and sepiolite-based fluids have been autoclaved at temperatures in the range from 70-800°F with the addition of chlorides and hydroxides of Na, K, Ca, and Mg. The rheological properties (apparent and plastic viscosity, fluid loss, gel strength, yield point, and cake thickness) of the autoclaved fluids have been studied and correlated with the chemical and physical changes that occur in the clay minerals during the autoclaving process. Both attapulgite and sepiolite particles start out with fibrous morphology and electrostatically neutral structures, and above 300°F, both begin to convert into a smectite with a flaky morphology and with an electrostatically charged structure. The conversion rate increases with the higher temperatures and at 600°F attapulgite becomes fully converted to a smectite, whereas, at that temperature about 20% of the sepiolite still survives the reaction.

THERMAL CONDUCTIVITIES OF AQUEOUS FOAM, W. D. Drotning, A. Ortega, and P. E. Havey, SAND82-0742, Sandia National Laboratories.

Thermal conductivity plays an important part in the response of aqueous foams used as geothermal drilling fluids. The thermal conductivity of these foams was measured at ambient conditions using the thermal conductivity probe technique. Foam densities studied were from 0.03 to 0.2 g/cm³, corresponding to liquid volume fractions of the same magnitude. Microscopy of the foams indicated bubble sizes in the range 50-300 micrometers for nitrogen foams, and 30-150 micrometers for helium foams. Bubble shapes were observed to be polyhedral at low foam densities and spherical at the higher densities. The measured conductivity values ranged from 0.05 to 0.12 W/m-K for the foams studied. The predicted behavior in foam conductivity caused by a change in the conductivity of the discontinuous gas phase was observed using nitrogen or helium gas in the foams. Analysis of the probe response data required an interpretation using the full integral solution to the heat conduction equation, since the thermal capacity of the foam was small relative to the thermal mass of the probe. The measurements of the thermal conductivity of the foams were influenced by experimental effects such as the probe input power, foam drainage, and the orientation of the probe and test cell. For nitrogen foams, the thermal conductivity vs liquid volume fraction was observed to fall between predictions based on the parallel ordering and Russell models for thermal conduction in heterogeneous materials.

STUDIES OF THE FRICTIONAL HEATING OF POLYCRYSTALLINE DIAMOND COMPACT DRAG TOOLS DURING ROCK CUTTING, SAND80-2677, A. Ortega and D. A. Glowka, Sandia National Laboratories.

A numerical-analytical model is developed to analyze temperatures in polycrystalline diamond compact (PDC) drag tools subject to localized frictional heating at a worn flat area and convective cooling at exposed lateral surfaces. Experimental measurements of convective heat transfer coefficients of PDC cutters in a uniform crossflow are presented and used in the model to predict temperatures under typical drilling conditions with fluid flow. The analysis compares favorably with measurements of frictional temperatures in controlled cutting tests on Tennessee marble. It is found that average temperatures at the wearflat contact zone vary directly with frictional force per unit area and are proportional to the one-half power of the cutting speed at the velocities investigated. Temperatures are found to be much more sensitive to decreases in the dynamic friction by lubrication than to increases in convective cooling rates beyond currently achievable levels with water or drilling fluids. It is shown that use of weighted drilling fluids may actually decrease cooling rates compared to those achieved with

pure water. It is doubtful that tool temperatures can be kept below critical levels (750°C) if air is employed as the drilling fluid. The degree of tool wear is found to have a major influence on the thermal response of the friction contact zone, so that for equal heating per contact area, a worn tool will run much hotter than a sharp tool. It is concluded that tool temperatures may be kept below critical levels at bit rotational speeds on the order of 100 RPM with conventional water cooling as long as the fluid provides good cutter-rock lubrication. At speeds on the order of 1000 RPM it is doubtful that temperatures can be kept subcritical, even with good lubrication, unless direct forced cooling of the friction contact zone can be achieved.

C. Borehole Mechanics

GEOHERMAL WELL COMPLETIONS: A SURVEY AND TECHNICAL EVALUATION OF EXISTING EQUIPMENT AND NEEDS, SAND82-7052, James E. Nicholson, Foster-Miller, Inc., Robert E. Snyder, Completion Technology Corporation, under contract to Sandia National Laboratories.

The geothermal environment and associated well completion problems are reviewed. Existing well completion equipment is surveyed and limitations are identified. A technical evaluation of selected completion equipment is presented. The technical evaluation concentrates on well cementing equipment and identifies potential failure mechanisms which limit the effectiveness of these tools. Equipment employed in sand control, perforating, and corrosion control are identified as potential subjects for future technical evaluation.

MECHANISMS OF FORMATION DAMAGE IN MATRIX PERMEABILITY GEOTHERMAL WELLS, SAND81-7208, J. L. Bergosh, R. B. Wiggins, D. O. Enniss, Terra Tek, Inc., under contract to Sandia National Laboratories.

Tests were conducted to determine mechanisms of formation damage which can occur in matrix permeability geothermal wells. Two types of cores were used in the testing, actual cores from the East Mesa Well 78-30RD and cores from a fairly uniform generic sandstone formation. Three different types of tests were run.

The East Mesa cores were used in the testing of the sensitivity of cores to filtrate chemistry. The tests began with the cores exposed to simulated East Mesa brine and then different filtrates were introduced and the effects of the fluid contrast on core permeability were measured. The East Mesa cores were also used in the second series of tests which tested formation permeability during long-term exposure to fluids. The generic sandstone cores were used in the third test series which investigated the effects of different sizes of entrained particles in the fluid. Tests were run with both single-particle sizes and distributions of particle mixes.

In addition to the testing, core preparation techniques for simulating fracture permeability were evaluated. Three different fracture formation mechanisms were identified and compared. Measurement techniques for measuring fracture size and permeability were also developed.

D. Diagnostic Technology

A 250°C PROTOTYPE ACOUSTIC INSTRUMENT FOR CEMENT BOND LOGGING, Hsi-Tien Chang, Sandia National Laboratories, Proceedings, 57th Annual Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, September 26-29, 1982, New Orleans, Louisiana, SAND82-0580.

The existing logging instruments developed for the oil and gas industry in general lack high-temperature capabilities. This deficiency results from the fact that high-temperature oil and gas reservoirs are seldom encountered in today's exploration. The temperature capabilities of most commercial electronic components are also one limiting factor for the high-temperature instruments. However, a steam injection well, a deep oil and gas well, or a geothermal well, do require downhole logging instruments capable of operation at high temperature. Such high-temperature wells could constitute an increasing portion of the production wells in the near future. For a successful operation of such high-temperature wells, the casing integrity and cement conditions must be accurately determined. It is the purpose of this paper to demonstrate the feasibility of designing an acoustic instrument for cement bond logging for operation at temperatures up to 250°C, using current technologies. This paper will first introduce an innovative technique to design an electronic circuit for high-temperature operation. This circuit consists mainly of commercial components and a Sandia-designed, long-life Sprytron switching tube. Temperature test results of each individual component and the complete circuit will be presented. The problems encountered and the solutions used to overcome these problems in Sandia's R&D effort on the design of a long-life Sprytron tube will be revealed. A 2V Permendur is used as a transmitter, and a piezoelectric material is used as a receiver.

High-temperature characteristics of these materials will be described. The design of an acoustic isolator and mechanical housing for this instrument will also be discussed. Selections of high-temperature O-rings and acoustic coupling fluids will be reviewed. Laboratory test data of the entire system will be shown, and the meanings of the received signal will be examined. Finally, a plan for field testing will be addressed.

A HIGH-TEMPERATURE PROTOTYPE INSTRUMENT FOR DOWNHOLE ACOUSTIC SENSING, SAND82-2893, Hsi-Tien Chang, Sandia National Laboratories, Proceedings, 1983 International Geoscience and Remote Sensing Symposium (IGARSS'83), August 31-September 2, 1983, San Francisco, California, IEEE.

Exploration resulting in a "non-productive" dry hole constitutes the main frustration in oil, gas or geothermal energy

development. Since extensive surface electromagnetic and seismic surveys usually are conducted prior to drilling, operators have reason to believe that a reservoir exists in the general area. However, the inability to pinpoint an existing reservoir fracture system (into which a well can be drilled) appears to be the main deficiency of these surface survey techniques. The low frequencies used in the surface surveys have limited resolution and cannot identify a fine subsurface structure.

This paper will discuss the feasibility of modifying a Sandia-designed cement bond instrument for fracture mapping. Instead of using a single tubular receiver, multiple receivers facing at different azimuthal angles can be used to identify directions of fracture reflections. The location of a fracture may be determined by the time delay and the signal strength of the acoustic returns. Frequencies selected for this application range from 10 KHz to 40 KHz. At these frequencies, this proposed instrument can provide a much better resolution and a much higher data rate than the conventional seismic surveys. The proposed instrument is designed to operate from room temperature to 250°C.

HIGH-TEMPERATURE ELECTRONICS COMPONENTS AND CIRCUIT DESIGNS, SAND81-2505C, Hsi-Tien Chang, Sandia National Laboratories, Proceedings, 32nd Electronic Components Conference, Components, Hybrids and Manufacturing Technology, Society of IEEE and Electronic Industries Association, May 10-12, 1982, San Diego, California.

Downhole logging instruments for geothermal application must have electronic circuits capable of operating from room temperature to 250°C. Previous research was centered on low voltage/low current hybrid microcircuits. However, a non-destructive evaluation (NDE) instrument for geothermal wells requires a circuit than can be operated at high voltage and high current in order to provide high-power output. In designing such a circuit, Sandia Laboratories is developing a high-power, high-speed, cold-cathode switching tube to be used as a substitute for SCRs or thyratrons. The possibility of using low-leakage JFETs beyond their rated temperature in a circuit design will be discussed. Commercial high-temperature components will be reviewed.

PROCEEDINGS--HIGH TEMPERATURE ELECTRONICS AND INSTRUMENTATION CONFERENCE--December 1981, SAND82-0425, Sandra R. Hudson, James R. Kelsey, Editors, February 1982.

This report presents the results of a two-day conference which reviewed the state-of-the-art and recent progress in High

Temperature Electronics and Instrumentation. The meeting was held at the Marriott at the Astrodome in Houston, Texas, December 7-8, 1981, and was sponsored by Sandia National Laboratories in conjunction with the U. S. Department of Energy, the University of Houston, and the IEEE. Over 300 attendees participated in this seminar which had sessions on Electronic Devices, Hybrid Microelectronics, 200°C Commercial Hybrids, and High Temperature Logging Cables and Package Materials. In addition to the technical sessions, industry participants exhibited their latest materials and components. This meeting was essentially a "graduation" exercise since Sandia National Laboratories and the Department of Energy have essentially completed their program in the High Temperature and Instrumentation Program; this conference served as a vehicle to transfer this technology to industry participants.

E. Systems Analysis/Program Summaries

A FORECAST OF GEOTHERMAL DRILLING ACTIVITY, A. J. Mansure and G. L. Brown, The BDM Corporation, under contract to Sandia National Laboratories, SAND82-7012.

This report forecasts the number of geothermal wells that will be drilled to support electric power production in the United States through 2000 A.D. Results of the forecast are presented by five-year periods for the five most significant geothermal resources.

GEOTHERMAL COMPLETION TECHNOLOGY LIFE CYCLE COST MODEL (GEOCOM), A. J. Mansure, et al., The BDM Corporation, under contract to Sandia National Laboratories, SAND82-7006.

GEOCOM is a model developed by BDM to evaluate the cost effectiveness of alternative technologies used in the completion, production, and maintenance of geothermal wells. The model calculates the ratio of life cycle costs to life cycle production and thus is appropriate for evaluating the cost effectiveness of a geothermal well even when the most economically profitable geothermal well does not have the lowest capital costs.

The results of the GEOCOM project are threefold: the establishment of a database for studying geothermal completions, the development of the GEOCOM model, and preliminary case-sensitivity studies. The GEOCOM code, documented in the BDM technical report BDM/A-81-618-TR, has the database built into its structure in the form of default parameters. These parameters include geothermal resource characteristics; costs of geothermal wells, workovers, and equipment; and other data. The data for the cost of geothermal wells were taken from the generic geothermal wells developed by Dr. B. J. Livesay. The basis for establishing workover parameters was a series of geothermal workover studies done by Paul McKissen of the Keplinger Operating Company.

THE USA PROGRAM IN GEOTHERMAL DRILLING AND COMPLETION RESEARCH AND DEVELOPMENT, SAND81-1795, C. C. Carson and B. C. Caskey, Sandia National Laboratories, Proceedings, International Conference on Geothermal Energy, BHRA Fluid Engineering, May 11-14, 1982, Florence, Italy.

The U. S. Department of Energy-sponsored program in geothermal drilling and completion research and development is managed by Sandia National Laboratories. The program objective is to conduct long-range R&D aimed at developing advanced geothermal drilling and completion systems to expand resource utilization. The program is organized into four broad

categories: 1) rock penetration mechanics, 2) drilling fluids, 3) borehole mechanics, and 4) diagnostics technology. Although much effort has been concentrated on bit development under rock penetration mechanics, current work focuses on understanding the limitations of drag bits as they apply to high speed drilling systems. Other technologies being pursued include cavitating jets and percussion systems as well as more exotic rock penetration techniques.

Fluid technology R&D addresses the high temperature, high corrosion and abnormal pressure problems found in geothermal areas. A high temperature clay based mud has been developed; current emphasis includes 1) developing on-site inert gas (nitrogen) generators, and 2) studying and testing high temperature stable aqueous foams.

The R&D in borehole mechanics addresses the problems of lost circulation and lining and cementing the well, as well as problems of production maintenance such as perforating and scale removal. An unique high temperature lost circulation/cementing test facility is under construction which will provide data on advanced materials and techniques for controlling lost circulation and cementing casing.

Well logging and downhole instrumentation R&D activities are organized under the diagnostics technology program element. The major thrust is in developing high-temperature electronic components, transducers and concomitant materials. A wellbore inertial navigator is also being developed. This paper presents the accomplishments of the program, and the status of current projects and plans for future activities.

THE IMPACT OF COMMON COMPLETION AND WORKOVER ACTIVITIES ON THE EFFECTIVE COSTS OF GEOTHERMAL WELLS, SAND82-0671C, C. C. Carson, Sandia National Laboratories, A. J. Mansure, The BDM Corporation, Proceedings, SPE Annual Meeting, Society of Petroleum Engineers, September 26-29, 1982, New Orleans, Louisiana.

Drilling and completing wells at minimum initial cost may not be the most cost effective way to exploit the geothermal resource. The impacts of completion practices on production and maintenance costs must also be considered. To evaluate alternative completion and workover technologies, a simple model has been developed that compares total well cost to total production or injection. This paper briefly discusses the model and focuses on results from its application to different completion and workover strategies.

GEOHERMAL COMPLETION TECHNOLOGY LIFE-CYCLE COST MODEL (GEOCOM), C. C. Carson, Sandia National Laboratories, A. J. Mansure, The BDM Corporation, SAND82-1435C, Proceedings, 1982 Annual Meeting, Geothermal Resources Council, October 11-14, 1982, San Diego, California.

GEOCOM is a model developed to evaluate the cost effectiveness of alternative technologies used in the completion, production, and maintenance of geothermal wells. The model calculates the ratio of life-cycle cost to lifecycle production or injection and thus is appropriate for evaluating the cost effectiveness of a geothermal well even when the most economically profitable well completion strategies do not result in lowest capital costs. The project to develop the GEOCOM model included the establishment of a data base for studying geothermal completions and preliminary case/sensitivity studies. The code has the data base built into its structure as default parameters. These parameters include geothermal resource characteristics; costs of geothermal wells, workovers, and equipment; and other data.

THE IMPACT OF COMMON PROBLEMS IN GEOHERMAL DRILLING AND COMPLETION, SAND82-1374C, C. C. Carson, Y. T. Lin, Sandia National Laboratories, GRC 1982 Annual Meeting, Geothermal Resources Council, October 11-14, 1982, San Diego, California.

Problems that arise in geothermal drilling and completion account for a significant portion of geothermal well costs. In order to evaluate new technologies for combatting these problems, the relative frequencies and severities of different problems have been estimated. The estimates were based on both subjectable judgments and analysis of available drilling records. The most common problems include lost circulation, stuck pipe and cementing, and their impact is to increase well cost by an average of at least 15%.

GEOHERMAL TECHNOLOGY DEVELOPMENT PROGRAM ANNUAL PROGRESS REPORT, SAND81-2124, October 1980-September 1981, James R. Kelsey, Editor, Sandia National Laboratories.

This report describes the status of ongoing Research and Development (R&D) within the Geothermal Technology Development Program. The work reported is sponsored by the Department of Energy/Division of Geothermal Energy (DOE/DGE), with program management provided by Sandia National Laboratories. The program emphasizes research in rock penetration mechanics, fluid technology, borehole mechanics, and diagnostics technology.

REPRESENTATIVE WELL MODELS FOR EIGHT GEOTHERMAL RESOURCE AREAS,
SAND81-2202, B. J. Livesay, Livesay Consultants; Y. T. Lin,
C. C. Carson, Sandia National Laboratories.

Representative well models have been constructed for eight major geothermal resource areas. The models define representative times and costs associated with the individual operations that can be expected during drilling and completion of geothermal wells. The models were made for and have been used to evaluate the impacts of potential new technologies. The nature, construction, and validation of the models are presented.

II. MAGMA ENERGY

Introduction

The world's geothermal energy resources exist in a variety of forms: dry steam, hot water, geopressured water, hot/dry rock, thermal gradients in the earth's crust, and magma. The objective of the Magma Energy Research Project now underway at Sandia National Laboratories with U. S. Department of Energy funding is to investigate the scientific feasibility of extracting energy directly from deeply buried circulating magma sources.

Significant amounts of thermal energy must exist in igneous-related systems in the upper 10 km of the crust of the world. In the western United States, Smith and Shaw (1979) estimate that 10^{23} J (10^5 quads) of thermal energy exist in evaluated young igneous-related systems within the 10 km depth. Of these systems, they estimated about two-thirds probably still have magma chambers with large molten fractions. This energy resource represents approximately 800+ times the total annual energy consumption in the United States. Smith and Shaw further estimate that the extent of thermal energy contained in unevaluated igneous-related systems will be at least 10 times the amount in the systems they evaluated.

Any program devoted to tapping the energy of a buried magma source is considered long-term and high risk because of the technological problems to solve and the many unknowns to resolve. The program at Sandia, under funding by the Division of Basic Energy Sciences of the DOE, emphasizes the investigation of basic scientific and engineering questions of energy extraction from magma; it is not structured toward early on-line power production from these geothermal resources.

To evaluate the scientific feasibility of extracting energy from magma bodies, the research program was divided into five areas: 1) Resource Location and Identification, 2) Source Tapping, 3) Magma Characterization, 4) Materials Compatibility, and 5) Energy Extraction. Laboratory and field research done at universities, the U.S. Geological Survey and at Sandia in the five areas determined that tapping magma for energy was indeed scientifically feasible. That conclusion, reviewed by independent research groups, then led to termination of this research program. The next step, not currently supported, is an evaluation of the engineering feasibility of energy extraction from magma systems.

A. Source Location and Definition

MAGMA SOURCE LOCATION SURVEY, SAND82-0219, H. C. Hardee, J. C. Dunn, J. L. Colp, Sandia National Laboratories.

A survey of industry/university geophysicists was conducted to obtain their opinions on the existence of shallow (less than 10 km from surface) magma bodies in the western conterminous United States and methods for locating and defining them. Inputs from 35 individuals were received and are included. Responses were that shallow magma bodies exist and that existing geophysical sensing systems are adequate to locate them.

THE RESONANT ACOUSTIC PULSER--A CONTINUOUS-FREQUENCY MARINE SEISMIC SOURCE, H. C. Hardee, R. G. Hills, Sandia National Laboratories, SAND80-2568J, Geophysics, in press.

A marine seismic source is described which produces a continuous low frequency (10-100 Hz) harmonic signal. High acoustic power levels (approximately 20 kW) are reached by using a resonant system. The seismic source has been successfully tested in lake and ocean environments.

PERIODIC DOWNHOLE SEISMIC SOURCES, SAND81-1891, H. C. Hardee, Sandia National Laboratories, Geophysical Prospecting, Vol. 31, pp 57-71 (1983).

Downhole periodic seismic sources offer a number of advantages over conventional sources including: good economics, high temperature applications, effective coupling of seismic waves directly into the region of interest, and sophisticated signal processing possibilities.

B. Magma Characterization

PERMEABLE CONVECTION ABOVE MAGMA BODIES, Tectonophysics, Vol. 84, pp 179-195, 1982, H. C. Hardee, Sandia National Laboratories.

Thermal convection above large shallow magma bodies in the crust is treated as a one-dimensional bottom-heated convection process in permeable media. Solutions for single-phase convection are briefly reviewed and a solution is developed for two-phase permeable convection in bottom heated media. Heat flow measurement techniques are discussed for permeable geologic zones above magma bodies and these techniques give consistent results for solidifying lava lakes in Hawaii (Kilauea Iki, $q = 260 \text{ kW/m}^2$) and Iceland (Heimaey, $q = 470 \text{ kW/m}^2$).

The heat loss from a magma body is a strong function of the permeability when a two-phase convection zone occurs above the magma body, and the heat loss is independent of the thickness of the two-phase convection zone. In steady-state two-phase convection zones, where permeability does not vary appreciably with depth, convective heat flow restrictions tend to limit the maximum saturation temperatures at depth to around 250°C -- an effect observed in many geothermal steam fields. A conduction dominated transition zone tends to occur between the two-phase zone and the magma body and the thickness of this transition zone may readily range from a few meters to several kilometers, depending on the permeability.

INCIPIENT MAGMA CHAMBER FORMATION AS A RESULT OF REPETITIVE INTRUSIONS, Bulletin Volcanologique, Vol. 45-1, H. C. Hardee, Sandia National Laboratories.

An analytical solution for periodic magma intrusions in conduits was developed to study the onset of shallow magma chamber formation. The solution is based on determining when a repetitive series of intrusions can cause the wall rock of a conduit to reach its melt temperature. The results show that magma chamber formation in conduits is a strong function of the volume rate of intrusion and that magma chamber formation is likely when the intrusion rate exceeds $10^{-3} \text{ km}^3/\text{yr}$, which agrees with observations by other investigators. Once this critical value of intrusion rate is reached, magma chambers are likely to begin forming after only a few intrusive pulses (less than ten). Results for both cylindrical conduits and dikes show that cylindrical conduits are more favorable for the formation of shallow magma chambers.

THE EFFECT OF MOLYBDENUM AND MOLYBDENUM PLUS CHROMIUM ON THE CORROSION OF IRON-, NICKEL-, AND COBALT-BASE ALLOYS IN BASALTIC LAVA AND SIMULATED MAGMATIC GAS AT 1150°C, SAND82-7055, Stephen A. Ehrlich and D. L. Douglass, University of California, Los Angeles, under contract to Sandia National Laboratories.

The compatibility of several binary and ternary alloys in a magma environment was studied. Binary alloys containing molybdenum and ternary alloys containing chromium and molybdenum were exposed to basaltic lava at 1150°C for periods of 24 and 96 hours. A cover gas was used to produce oxygen and sulfur fugacities corresponding to those of the gases dissolved in basaltic melts. Three base metals were used. These included iron, nickel, and cobalt. The primary reactions in binary alloys were found to be sulfidation. Oxide scales with a spinel layer formed on ternary alloys. The synergistic effect of molybdenum and chromium additions in ternary alloys exhibited superior corrosion resistance to binary alloys which formed base-metal sulfides down grain-boundaries. Extensive analyses of the reaction products by scanning electron microscopy, X-ray energy dispersive analysis, electron microprobe analysis, and metallography are presented for each alloy. The products formed are discussed with reference to thermodynamic stability diagrams, and the reaction path concept is used to explain some of the corrosion.

CONVECTIVE TRANSPORT IN CRUSTAL MAGMA BODIES, SAND82-0907J, Journal of Volcanology and Geothermal Research, H. C. Hardee, Sandia National Laboratories.

Convective transport in enclosures is reviewed as it relates to magma bodies. Convective effects are discussed that are peculiar to the rheological character of magma. The large Prandtl number of magma delays onset of turbulence and causes velocity disturbances to extend far beyond the thermal boundary layer and well into the fluid core. A boundary layer analysis is used to show that convective transport in enclosed magma bodies produces a significant upward heat flux which can lead to migration of magma by upmelting. Multicellular convection is discussed and shown in some cases to produce upflow at the walls which can lead to vertical zonation and layering. Oscillatory convective circulation examples are given and this phenomena is discussed as a possible mechanism for eruption cycles and for vertical zonation in magma chambers. Non-Newtonian rheology which can also be another mechanism for layering, is also examined.

KILAUEA IKI LAVA LAKE: GEOPHYSICAL CONSTRAINTS ON PRESENT (1980) PHYSICAL STATE, Journal of Volcanology and Geothermal Research, Vol. 13, No. 1-2, pp 31-61, 1982, J. L. Colp, Sandia National Laboratories, John F. Hermance, Brown University.

A model is presented representing the present-day (1980) configuration of Kilauea Iki lava lake. This interpretation is a synthesis of the results of drilling, thermal modeling, petrology and geophysical sensing experiments. According to this model, the crust of the lava lake is characterized by a thick two-phase convection-dominated zone and a single-phase (steam) dry-out zone. Geophysical measurements (namely electromagnetic sounding experiments) suggest the presence of an anomalous zone which is significantly thicker (greater than 30 m thick at 40 m depth) than the zone of melt-slush (10 m thick at 54 m depth) seen in petrological investigations of the drill core. This suggests that the geophysically active zone is caused by physical processes not directly related to the presence of magma or that the magma is thinly disseminated over a broader region than indicated in petrological inspections of recent (1979) drill cores. We cannot at this time rule out (or support) the possibility of a plexus of segregation veins distributed throughout the high-temperature region of the lake, particularly below the melt slush region where information is sparse.

COMMENTS ON PERMEABLE CONVECTION ABOVE MAGMA BODIES, H. C. Hardee, Sandia National Laboratories, Tectonophysics, in press.

The lava lake calculations by Hardee (1982) require the presence of water. This water may well have reached the lava lake in the form of rainfall or condensation. In addition to the presence of water, the permeability and thermal properties of lava and water are used to evaluate the rate of two-phase convection heat flow (268 W/m^2). This calculation agrees well with two independent heat flow calculations - 257 W/m^2 based on temperature gradient measurements in the non-convecting transition zone and 243 W/m^2 based on the rate of solidification as determined from repeatedly drilling to the melt interface over a number of years. In addition, the permeability was determined in an independent measurement in a packed-off pressurized borehole. The two-phase convective heat flow analysis used by Hardee, which showed that heat flow is a function of permeability, has been verified by careful laboratory experiments by the author and by independent laboratory measurement by others. Finally, the lava bodies at Kilauea Iki, Hawaii, and Heimaey, Iceland, show similar solidification behavior and rates and these bodies are of similar material, age and permeability. The rainfall is considerably different for these two regions however. Kilauea Iki lava lake is situated in the Ohia Rain Forest and receives considerably more rainfall than Heimaey. Yet the solidification rate at Heimaey, instead of being much smaller than that of Kilauea Iki, is actually twice

as large. This is not consistent with a solidification model based on amount of rainfall. While rainfall may be important in the early stages of lava lake solidification when the crust is thin, rainfall does not appear to be a primary factor in the pseudo-steady mature solidification stage of lava lakes.

C. Energy Extraction

ENERGY EXTRACTION FROM CRUSTAL MAGMA BODIES, SAND82-1386A, J. C. Dunn, Sandia National Laboratories, ASME-JSME Thermal Engineering Joint Conference, March 20-24, 1983, Honolulu, Hawaii.

The DOE-funded Sandia Magma Energy Research Project has been investigating methods of extracting thermal energy directly from shallow magma systems within the crust. Heat transfer to a closed heat exchanger inserted into a magma body has been studied extensively. This has included analytical heat transfer studies, materials survivability testing, laboratory measurements of convective properties of magma, and field measurements in a flowing lava river and in a ponded lava lake. These studies have led to the conclusion that closed heat exchangers can be placed in a fluid magma body and that useful amounts of energy can be extracted for long periods of time. Energy extraction rates are comparable to conventional hot water or steam geothermal systems.

GASEOUS FUEL GENERATION BY MAGMA-THERMAL CONVERSION OF BIOMASS, SAND82-0301J, Journal of Energy, in press, T. M. Gerlach, H. C. Hardee, Sandia National Laboratories.

A wide range of upper crustal magma bodies provide suitable thermal energy sources for conversion of water biomass mixtures to higher quality gaseous fuels. The compositions, concentrations, and energy contents of the generated fuel gases are relatively insensitive to the type of magma body, but the rates at which fuels can be generated is strongly dependent on magma type. Fuel generation rates for basaltic magmas are at least 2-3 times greater than those for andesitic magmas and 5-6 times those for rhyolitic magmas. CH₄ is the main gas that can be generated in important quantities from magma thermal energy under most circumstances. CO is never important, and significant H₂ generation is restricted to shallow basaltic magmas.

D. Project Reviews/Summaries

FY-80 ANNUAL PROGRESS REPORT--MAGMA ENERGY RESEARCH PROJECT, SAND81-0100, J. L. Colp, Editor, Sandia National Laboratories.

The objective of the Magma Energy Research Project is to determine the scientific feasibility of extracting energy from magma bodies. Project activities are divided into five individual tasks representing all aspects of the concept.

Task I -- Resource Location and Definition. A joint Sandia/USGS geophysical sensing experiment was performed at Kilauea Iki lava lake. The seismic experiments suggested the presence of three reflectors; continued analysis of the data is required to discern definitive depths. Electromagnetic profiling experiments did not seem to show significant differences in the total volume of the inferred molten zone when compared to the 1976 data. A heat transfer model of a hydrothermal, hot dry-out zone, and melt zone of a lava lake was developed and verified by in situ measurements.

Petrologic analysis of Kilauea Iki cores from the 1979 drill holes was continued. Some results were: 1) the melt lens contained a maximum of 35% silicate liquid, 7 m of it had greater than 25% liquid; 2) the liquid trends continuously from basaltic to rhyolitic, this was inferred to be a product of in situ crystallization.

Task II -- Source Tapping. Triaxial mechanical testing of water saturated granodiorite, basalt, and andesite to 1000°C and 3 kb was completed. A water weakening effect was noticed only in andesite only at temperatures over 850°C. Brittle failure occurred in dry and saturated systems suggesting that boreholes will be stable at 5010 km depth.

Task III -- Magma Characterization. The characterization of volcanic-magmatic gases for basaltic and alkaline lavas was completed, and a data base of C-O-H-S-Cl gas compositions typical of mafic lavas is now available for material compatibility studies. Petrographic computer codes were developed and used to reduce microprobe analyses to classify glasses and to calculate mineral composition of igneous rock core.

Task IV -- Magma/Material Compatibility. Preliminary results from evaluations of 15 pure metals and 16 alloys in low pressure, simulated magma environments suggest that: 1) the chromium content of both ferritic and austenitic stainless steels is the most important factor in providing corrosion resistance; 2) Type 310 is by far the most corrosion-resistant alloy of any of the commercial stainless steels.

Task V -- Energy Extraction. Performed heat extraction calculations for a closed heat exchanger in various hypothetical magmas. These included the effects of high Prandtl

number, crust formation, curvature effects, laminar/turbulent transition, and non-Newtonian rheology. Laboratory tests on convection heat transfer measurements in basalt were initiated and gave convective heat transfer rates of 30 kW/m^2 in 1290°C basalt.

MAGMA ENERGY, THE ULTIMATE HEAT SOURCE FOR GEOTHERMAL FIELDS, Vol. 11, No. 7, pp 3-7 (1982), GRC Bulletin, H. C. Hardee, Sandia National Laboratories.

Magma, or molten rock, is the ultimate heat source for geothermal fields. In conventional geothermal applications the energy from magma is tapped indirectly in natural geothermal fields that are associated with certain magma bodies. Many magma sources, however, lack an adequate geothermal field for exploitation. Enormous quantities of energy are stored in magma bodies in the crust. The portion of this energy that can be tapped in conventional geothermal fields is a small fraction of the total energy available in crustal magma sources. The bulk of this untapped reserve of magma energy would become available if methods were found for extracting energy directly from magma. Appreciable amounts of magma are believed to exist at depths shallow enough to be directly tapped. In the United States the magma resource is estimated at 10^{23} to 10^{24} J within the upper 10 km of the crust. This is equivalent to a 1,000-10,000 year total energy supply for the country. The bulk of this magma resource is in the conterminous western United States. An additional magma resource in the oceanic spreading centers of the circum-Pacific region is many times larger.

MAGMA ENERGY UTILIZATION, SAND82-1046A, H. C. Hardee, Sandia National Laboratories, ASME-JSME Special Session on Heat and Mass Transfer in Underground Media, May 12, 1982, Washington, DC, March 13-16, 1983, Honolulu, Hawaii.

The evidence accumulated over the past six years of the Magma Energy Research Project has established that it is scientifically feasible to extract energy from potentially extensive sources of molten magma deposits in the crust. The USGS estimates of the amount of the magma resource in the upper 10 km of the continental western United States corresponds to a quantity of energy equivalent to 1,000- 10,000 times the annual U.S. energy consumption. The magma resource in the mid-oceanic ridges is at least an order of magnitude larger.

Studies and laboratory and field data indicate that it is scientifically feasible to drill into a magma body, keep the hole open, and extract useful energy. Related field experiments have been conducted in lava lakes and at volcanic

eruption sites. Calculations and experiments show that when a closed heat exchanger is placed in contact with molten magma, natural convection is induced adjacent to the heat exchanger surface. This convection process leads to steady heat extraction rates of 10-50 kW/m² which are comparable to conventional geothermal production rates. Field tests of advanced open heat exchanger systems, where water and steam mix directly with magma, have produced heat extraction rates an order of magnitude greater than those with closed heat exchangers. Both the molten magma and the hot margin zones surrounding magma bodies can be tapped for energy. The thermal energy derived from magma sources can be used to produce fuels as well as electricity.

MAGMA ENERGY RESEARCH PROJECT, H. C. Hardee, Sandia National Laboratories, International Power Generation, Vol. 5, No. 4, pp 22-27 (1982).

Magma is regarded as a long-range energy source, but one of such magnitude that it merits careful investigation. U. S. Geological Survey scientists estimate that the energy content of magma bodies within 10 km (six miles) of the earth's surface in the continental U.S. is 800-8000 times the present annual U.S. energy consumption. Major magma bodies are in the western U.S.

Results of field tests conducted in late 1981 by the National Sandia Laboratories, Albuquerque, New Mexico, combined with earlier research indicate that it is scientifically feasible to extract thermal energy directly from the bodies of molten rock (magma) buried within 10 km of the earth's surface.

THE SEARCH FOR MAGMA, H. C. Hardee, Sandia National Laboratories, Geophysics: The Leading Edge of Exploration, Vol. 2, No. 3, pp 14-19 (1983).

Magma, or molten rock, is the ultimate heat source for geothermal fields. In conventional geothermal applications the energy from magma is tapped indirectly in natural geothermal fields usually associated with magma bodies. Many magma sources, however, lack an adequate geothermal field for exploitation. Enormous quantities of energy are stored in magma bodies in the Earth's crust. The portion of this energy that can be tapped in conventional geothermal fields is a small fraction of the total energy available in crustal magma sources.

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