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GEOTHERMAL TECHNOLOGY PUBLICATIONS AND RELATED REPORTS: A BIBLIOGRAPHY

January 1977 - December 1980

Sandra R. Hudson, Editor

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Sandra R. Hudson, Editor
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Abstract

This bibliography lists titles, authors, abstracts, and reference information for publications which have been published in the areas of Drilling Technology, Logging Instrumentation, and Magma Energy during the period 1977-1980. These publications are the results of work carried on at Sandia National Laboratories and their subcontractors for the U. S. Department of Energy, Divisions of Geothermal Energy, Basic Energy Sciences, and Fossil Fuel Extractions. Some work was also done in conjunction with the Morgantown, Bartlesville, and Pittsburgh Energy Technology Centers.

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A number of publications were made through the Geothermal Resources Council Transactions. The references for those transactions are listed below:

GEOTHERMAL ENERGY: A NOVELTY BECOMES RESOURCE, TRANSACTIONS, Volume 2, Geothermal Resources Council Annual Meeting, July 25-27, 1978, Hilo, Hawaii.

EXPANDING THE GEOTHERMAL FRONTIER TRANSACTIONS, Volume 3, Geothermal Resources Council Annual Meeting, September 24-27, 1979, Reno, Nevada.

GEOTHERMAL: ENERGY FOR THE EIGHTIES TRANSACTIONS, Volume 4, Geothermal Resources Council Annual Meeting, September 9-11, 1980, Salt Lake City, Utah.

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I. DRILLING TECHNOLOGY

Introduction

Access to natural resources by drilling is needed to evaluate and produce the resource. As fuels and minerals are depleted, demands on drilling technology are increased in order to access deeper or more difficult formations. For example, conventional oil and gas technologies are not adequate to economically drill into 300°C, hard rock, hostile environments of geothermal energy sources.

Sandia National Laboratories and its subcontractors have been developing drilling and well completion technology in support of the U. S. Department of Energy's programs in geothermal energy, oil and gas, and coal. The major emphasis has been to develop the technology to drill and complete wells in geothermal environments; Sandia manages the DOE Division of Geothermal Energy Program in this activity.

A. Drill Bit Technology

SINGLE POINT ROCK CUTTING STRENGTH AND FATIGUE EVALUATION OF GAS PRESSURE DIFFUSION BONDED STRATAPAX®, SAND77-1962, Charles F. Huff, Richard F. Ashmore, and J. Wayne Miller, Sandia National Laboratories.

Single point rock cutting experiments were conducted to test the competence of the diffusion bonding technique for attaching the General Electric polycrystalline diamond surfaced cutting element (Stratapax®) to a stud or bit blank. These tests showed that diffusion bonds which have shear strengths of over 65,000 psi at room temperature performed well in the long-term fatigue environment of cutting various granites on a vertical milling machine. These bonds proved to be superior to conventional low temperature braze bonds which fail because of frictional heating and bond erosion.

Before the bond tests were conducted, preliminary experiments were run to determine the response of the Stratapax as a cutting element in an actual rock cutting environment in order to facilitate the bond tests. These tests proved to be very informative in showing the effects of rake angle on Stratapax survival. With negative rake angles of less than 20°, the forces tangent to the face of the Stratapax cause spalling of the diamond which leads to eventual catastrophic failure of the entire assembly. With negative rake angles greater than 20° in the same rocks, the Stratapax did not spall or fail during normal cutting.

This report includes measured forces and visual observations of Stratapax while cutting granites, limestone, and sandstone. From the data collected on these tests, it was determined that with satisfactory attachment, the proper rake angle, and adequate cooling, Stratapax represents an extremely viable tool for cutting or drilling rock.

STRATAPAX® COMPUTER PROGRAM, SAND77-1994, Richard F. Ashmore, Sandia National Laboratories; Dr. K. W. Chase, and D. L. Mahlum, Brigham Young University, April 1978.

Correct placement of Stratapax cutters on a drill bit is of prime importance in order to equalize the volume of rock removed per revolution, to balance torque on the bit, and to equalize wear on the cutters. Initially, placement of the cutters was determined by graphical methods which were time consuming and limited in accuracy. Therefore, criteria for a computer program to perform this function were formulated by Sandia Laboratories personnel; the task of writing the computer program was assigned to a Brigham Young University Mechanical Engineering Professor. The resulting program has been further modified and expanded under contract with Brigham Young University. This effort has resulted in a program which computes the area of rock in contact with each Stratapax cutter, the volume removed per revolution, torque applied to each cutter, and the wear surfaces in contact with the rock. The program detailed in this memorandum is a powerful tool which can be used to design Stratapax drill bits and can also be adapted to other types of drill bits with circular cutters.

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A REVIEW OF ATTACHMENT OF STRATAPAX® USING GAS PRESSURE DIFFUSION BONDING, SAND78-0318C, J. L. Jellison and C. F. Huff, Sandia National Laboratories.

The development of the gas pressure diffusion bonding technique for attachment of Stratapax® diamond cutters to studs or bit blanks is reviewed in this paper. This paper updates the results presented previously on this continuing project at Sandia Laboratories conducted for the Division of Oil, Gas, Shale and In Situ Technology, Department of Energy.

The process has been developed to a point where bonded parts can be obtained from commercial suppliers. A complete description is given of the latest bonding process including surface conditioning, metallization, canning, and gas pressure bonding. Results from experiments designed to facilitate reliable fabrication are included. Bond strengths of samples obtained from commercial suppliers have shear strengths (500 MPa) comparable to those developed at Sandia Laboratories.

Results from laboratory drilling experiments are also included. These tests were run to demonstrate the reliability of the bond in a fatigue environment. With a suitable attachment technique and adequate cooling, the Stratapax has demonstrated superior cutting capabilities in rock with rates of penetration to 90 fph in Sierra White Granite.

DESIGN OF SPECIAL PERFORMANCE BITS UTILIZING SYNTHETIC DIAMOND CUTTERS, SAND78-0645, Charles F. Huff, Alan L. McFall, Jack A. St. Clair, Sandia National Laboratories, SPE Paper No. 7515, 53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Houston, Texas, October 1-4, 1978.

A new technique (diffusion bonding) for attaching synthetic, polycrystalline diamond cutters to drill bits has been developed by Sandia Laboratories with funding from the Department of Energy. To test the diffusion bonding technique and some new bit design concepts, Sandia is designing several types of special performance bits utilizing synthetic diamond compacts. Two all-compact bits, a hybrid diamond-compact/roller-cone bit, and two coring bits are being built for testing in laboratory and field environments. A special coring bit designed to operate with a pressure coring system and to be cleaned and cooled with a small quantity of low-invasion coring fluid is undergoing drilling tests. One configuration of the downhole replaceable chain drill utilizes synthetic diamond cutters at the pivot point, while a second configuration utilizes these cutters exclusively. This paper describes the design of each bit and presents the results of recent drilling tests. Design and testing philosophy are reviewed and plans for future design revisions and testing are described.

CONTINUOUS CHAIN DRILL BIT DEVELOPMENTS, SAND78-0669C, M. M. Newsom, J. A. St. Clair, H. M. Stoller, and S. G. Varnado, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 2, July 1978, p. 495, Hilo, Hawaii.

Under DOE's Geothermal Well Technology Program, the Continuous Chain Drill Bit, in which fresh cutting surfaces are cycled into place without removing the bit from the hole, is under development by Sandia Laboratories. Fixed heat bit testing has optimized cutting surface

diamond patterns, developed adequate bit hydraulics, and solved the apex problem through application of Stratapax® cutters in the bit nose. Prototype chain drill testing has demonstrated structural integrity, identified some hydraulic erosion and cycling mechanism, problems, and confirmed superior drilling rate and lifetime performance to commercial diamond bits when drilling hard abrasive rock.

BONDING TECHNIQUE ATTACHES STRATAPAX TO DRILL BITS, SAND78-1405J, C. F. Huff, J. L. Jellison, S. G. Varnado, OIL AND GAS JOURNAL, February 8, 1979, pp 111-114.

Use of man-made diamond compacts (e.g., General Electric tradename Stratapax) as cutters in drill bits offers potential for significantly improving penetration rates in many formations.

Several attempts have been made to utilize these cutters. However, techniques for attaching the cutters to the bit have proven inadequate in many cases. This has prevented the full utilization of the capability of the cutters and has frequently caused loss of cutters in the hole.

An improved technique for attaching Stratapax cutters to bit blanks or studs has been developed at Sandia Laboratories, Albuquerque. This work is being funded by the Drilling Technology Development Program of the Division of Oil, Gas, Shale, and In Situ Technology, U. S. Department of Energy. The procedure is now being transferred to commercial suppliers so that it will be available to a wide range of users.

The procedures used in implementing this attachment technique involve metallization of the surfaces to be bonded and placement of the parts in a high temperature, high pressure environment where diffusion bonding occurs. The resulting weld has a measured strength of between 60 and 80 kpsi/sq inch in pure shear tests. Single-point rock cutting tests and lab tests of a full-scale bit have shown good fatigue strength for the weld. Field tests of experimental bits are planned to demonstrate the integrity of the weld in an actual drilling environment.

RECENT DEVELOPMENTS IN DRILL BIT TECHNOLOGY, SAND79-0084C, S. G. Varnado, Sandia National Laboratories and B. E. Busking, Shell Internationale, The Hague, The Netherlands, Proceedings of Tenth World Petroleum Congress, Bucharest, Rumania, July 1979.

The drilling environment in deep oil and gas wells and in geothermal wells is generally hostile. Formation temperatures of 150-350°C are commonly encountered. New developments in drilling technology are required to reduce the cost of drilling wells under these conditions. In the United States, the Department of Energy is funding research directed at assisting industry in developing the techniques required for drilling in hostile environments. Among the most recent developments in high temperature drill bits are the use of Stratapax cutters in drag-type bits and the use of improved, high-temperature materials in conventional roller cone bits. The paper describes recent developments in these two areas.

DESIGN AND USE OF POLYCRYSTALLINE DIAMOND COMPACT DRAG BITS IN THE GEOTHERMAL ENVIRONMENT, SAND79-0364C, S. G. Varnado, C. F. Huff, P. Yarrington, Proceedings of Society of Petroleum Engineers of AIME, 54th Annual Technical Conference and Exhibition, Las Vegas, Nevada, September 23-26, 1979.

The potential for utilizing polycrystalline diamond compact (PDC) cutters to provide high performance bits has been recognized by the drilling industry. New bit designs suitable for geothermal drilling are being developed based on the results of single cutter laboratory tests and analytical analyses. A new bonding technique for attaching the cutters to the bit body has been developed. Bits using this new technique have been built and tested with promising results. The results of single cutter tests, the bit design philosophy, the bonding process for attaching the cutters to the bit body, and the results of laboratory and field tests of these new bit designs are described.

DEVELOPMENT AND TESTING OF A DOWNHOLE REPLACEABLE CONTINUOUS CHAIN DRILL, SAND79-0400C, S. G. Varnado, J. A. St. Clair, H. K. Togami, Sandia National Laboratories, Proceedings of 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, September 23-26, 1979.

The continuous chain drill is a diamond drill bit in which the cutting surface can be replaced while the bit is still in the hole. Successful field testing of this bit has recently been accomplished. This paper describes the development and testing of this prototype.

FIELD TEST RESULTS OF IMPROVED GEOTHERMAL TRICONE BITS, SAND79-0588A, A. B. Maish, Sandia National Laboratories, Proceedings of 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, September 23-26, 1979.

Terra Tek, Inc. has developed an improved third generation geothermal rollercone bit under a contract with Sandia Laboratories. A conventional rollercone bit design was improved by the selection of higher performance materials for crucial components. In September, 1978, six of the improved Terra Tek MK-III bits were field tested against the conventional bit design in a geothermal hole at The Geysers. The results of the field comparison test were analyzed to determine the improvement to bit life and penetration rate available with the new bit. The results indicate that the new bits have a substantially longer life and maintain hole gauge better than the conventional bits, but that they do not have a higher penetration rate. Details of the analysis and the results are given along with preliminary results of wear and metallurgical studies of the bits.

DEVELOPMENT OF HIGH PERFORMANCE BITS UTILIZING POLYCRYSTALLINE DIAMOND COMPACT CUTTERS, SAND79-0866C, C. F. Huff, S. G. Varnado, Proceedings of Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology, Tulsa, Oklahoma, August 22-24, 1979.

Sandia Laboratories is developing techniques for utilization of polycrystalline diamond compact (PDC) cutters on drill bits. A technique for attaching PDC cutters by a diffusion bonding process has been

developed. The application of the method for attaching cutters to mounting studs has been demonstrated. The final phase of this project is underway where the goal is to attach the cutters directly to the bit body eliminating the necessity for using studs. Development of high performance PDC bit designs, capable of drilling into hard formations at high penetration rates has begun. Laboratory and field tests have been conducted and additional tests are scheduled. This paper describes the recent advances made in cutter bonding and bit design technology. The most significant advance made in bonding technology in the last year is the attachment of PDC cutters to steel. The bonds to steel, which is the most desirable material for bit bodies, have shear strengths in excess of 60,000 psi. An investigation into the direct attachment of cutters to bit bodies is being conducted and a brief discussion of the bonding techniques and associated stress problems is given. The results of full-scale laboratory testing of a hybrid roller-cone PDC bit and a 6-1/2 inch PDC bit are described. These tests were conducted to evaluate the bonding technology and determine the effects of wear on bit performance. The effects of wear on required torque and bit weight for various cutter penetration up to 0.250 inch in granite are given. The first field test of a bit with diffusion bonded PDC cutters is described.

FIELD TEST RESULTS OF IMPROVED GEOTHERMAL TRICONE BITS, SAND79-1432C, A. B. Maish, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 409, Reno, Nevada.

The third generation geothermal tricone bit under development by Sandia Laboratories and Terra Tek was field tested in The Geysers geothermal area in California. Data taken during the tests were analyzed to determine the performance of the research bit as compared with the performance of a preferred tricone bit currently in use. An analysis of the bit gage wear, which is a major factor in bit life in this hard rock area, determined that the research bit had a 30 percent increase in gage life as compared with the conventional roller cone bit. Improvements in bearing and insert life were also measured. The optimal drilling run duration was determined for this formation as a function of reaming time and drilling time.

CONTINUOUS CHAIN BIT DEVELOPMENT, SAND79-1433C, J. A. St. Clair, F. A. Duimstra, S. G. Varnado, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 683, Reno, Nevada

The continuous chain drill is a diamond drill bit in which the cutting surface can be replaced while the bit is still in the hole. The first prototype of the chain drill system was fabricated and tested in 1977. Problems were encountered with the mechanism used to cycle the bit. A second prototype bit was designed to circumvent these problems. An accelerated development and test program has provided field test results on Prototype II in less than two years. Field testing at the Nevada Test Site has proven the feasibility of the downhole changing mechanisms. The development and testing of this prototype is described.

RECENT DEVELOPMENTS IN POLYCRYSTALLINE DIAMOND COMPACT DRILL BIT DESIGN, SAND79-1592A, C. F. Huff, S. G. Varnado, Sandia National Laboratories, Proceedings of Energy-Sources Technology Conference, Petroleum Division, American Society of Mechanical Engineers, New Orleans, Louisiana, February 3-7, 1980.

Development of polycrystalline diamond compact drill bits for use in severe environments is continuing at Sandia Laboratories. This effort consists of both analytical and experimental analysis which is described.

The experimental program is based on single point tests of cutters on a large vertical milling machine. Results of recent tests of cutters in this mode of operation are described. The primary purpose of these tests was to determine the effect of various cut cross sections including corners for both new and worn cutters.

The experimental program also includes laboratory tests of full scale bits and field tests of these designs. The laboratory tests at simulated downhole conditions yielded valuable parametric data that is not available from the field tests. Rate of penetration and torque versus weight on bit are given for several designs in various types of rock. Abrasive granite was used to wear the bits so that the effects of cutter dulling could be seen. The drilling under simulated downhole pressures was conducted at 2500 psi and 5000 psi along with tests at atmospheric pressure. The effects of pressure on drilling rates are shown.

Field tests of these bits are described. Valuable information on bit performance was gained although instrumentation was limited. The 7-7/8 inch hybrid bit drilled at rates of 50 fph with only about 180 gpm water flow for chip removal.

POLYCRYSTALLINE DIAMOND COMPACT DRAG BITS FOR GEOTHERMAL USE, SAND79-1836J, S. G. Varnado, C. F. Huff, P. Yarrington, Sandia National Laboratories, WORLD OIL, March 1980, pp 63-70.

The potential for utilizing polycrystalline diamond compact (PDC) cutters to provide high performance bits has been recognized by the drilling industry. New bit designs suitable for geothermal drilling are being developed based on the results of single cutter laboratory tests and analytical analyses. A new bonding technique for attaching the cutters to the bit body has been developed. Bits using this new technique have been built and tested with promising results.

RESULTS OF CHAIN BIT FIELD TESTS ARE PROMISING, SAND79-1837J, S. G. Varnado, J. A. St. Clair, H. K. Togami, Sandia National Laboratories, WORLD OIL, Vol. 189, No. 5, October 1979, pp 59-61.

The continuous chain drill is a diamond drill bit in which the cutting surface can be replaced while the bit is still in the hole. Successful field testing of this bit has recently been accomplished. This article describes the development and testing of the second prototype by Sandia Laboratories for the Department of Energy's Geothermal Drilling and Completion Technology Program.

DRILLING HORIZONTAL HOLES IN COAL BEDS FROM THE SURFACE WITH WATER JETS, SAND80-0057A, K. M. Timmerman, Sandia National Laboratories, Proceedings of 5th Symposium of the Rocky Mountain Fuel Society, Salt Lake City, Utah, February 21-22, 1980.

Holes drilled horizontally into coal beds from a vertical hole can be used to drain methane from gassy coal prior to mining and to link vertical wells for underground coal gasification. A device using high pressure water jets to drill those holes is being developed by Sandia Laboratories. The drilling head is lowered down a vertical hole on an articulated drill string, rotated to the horizontal at the coal seam and advanced into the coal.

First prototypes of the drilling head and the rotation mechanism have been built and tested. Holes with diameters between six and eight inches have been drilled at rates of one to two feet per minute for distances up to 35 feet.

DRILLING HORIZONTAL HOLES IN COAL BEDS FROM THE SURFACE WITH WATER JETS, SAND80-0115A, K. M. Timmerman, Sandia National Laboratories, Proceedings of Symposium on Unconventional Gas Recovery, Pittsburgh, Pennsylvania, May 18-21, 1980.

Holes drilled horizontally into coal beds from a vertical hole can be used to drain methane from gassy coal prior to mining and to link vertical wells for underground coal gasification. A device using high pressure water jets to drill those holes is being developed by Sandia Laboratories. The drilling head is lowered down a vertical hole on an articulated drill string, rotated to the horizontal at the coal seam and advanced into the coal.

Instruments in the drill string will provide hole pitch and azimuth data to the driller on the surface. An additional system, using natural gamma detectors, radar or sonar techniques, is being developed to locate the drilling head relative to the roof and floor of the coal seam while drilling. A pitch control on the drilling head, operable from the surface, will enable the driller to use this information to control drilling direction and keep the hole in the coal.

First prototypes of the drilling head and the rotation mechanism have been built and tested. Holes with diameters between six and eight inches have been drilled at rates of one to two feet per minute for distances up to 15 feet. Continuing development work is described.

LABORATORY AND FIELD TESTING OF IMPROVED GEOTHERMAL ROCK BITS, SAND80-7102, R. R. Hendrickson, R. W. Winzenried, A. H. Jones, Terra Tek, A. B. Maish, Sandia National Laboratories, Proceedings of ASME Energy Technology Conference, New Orleans, Louisiana, February 5-7, 1980; also Sandia National Laboratories report.

The development and testing of 222 mm (8-3/4 inch) unsealed, insert type, medium hard formation, high-temperature bits are described. The new bits were fabricated by substituting improved materials in critical bit components. These materials were selected on bases of their high temperature properties, machinability, and heat treatment response. Program objectives required that both machining and heat treating could be accomplished with existing rock bit production equipment.

Two types of experimental bits were subjected to laboratory air drilling tests at 250°C (482°F) in cast iron. These tests indicated field testing could be conducted without danger to the hole, and that bearing wear would be substantially reduced. Six additional experimental bits, and eight conventional bits were then subjected to air drilling at 240°C (464°F) in Franciscan Graywacke at The Geysers, California. The materials selected improved roller wear by 200 percent, friction-pin wear by 150 percent, and lug wear by 150 percent.

Geysers drilling performances compared directly to conventional bits indicate that in-gage drilling life was increased by 70 percent. All bits at The Geysers are subjected to reaming out-of-gage hole prior to drilling. Under these conditions the experimental bits showed a 30 percent increase in usable hole over the conventional bits. These tests demonstrated a potential well cost reduction of 4 to 8 percent. Savings of 12 percent are considered possible with drilling procedures optimized for the experimental bits.

Industrial participation in the program included Reed Rock Bit Company, Inc., which fabricated the prototype bits, and Union Geothermal Division of Union Oil Company, Inc., which provided the field drilling site. The program was funded by the U. S. Department of Energy, Division of Geothermal Energy, under the direction of Sandia Laboratories.

ECONOMIC ANALYSIS OF ADVANCED TECHNOLOGY BITS AND PICKS FOR A LONGWALL MINING SYSTEM, SAND80-7163, Leonard L. Felts, David P. Gabello, Fred P. Hayoz, TRW Energy Engineering Division, McLean, Virginia, December 1980.

The introduction of advanced technology longwall shearer bits, continuous miner picks and roof bolter bits into contemporary longwall mines was analyzed to determine the effect on machine productivity, capital investment and operating and maintenance costs. Parametric combinations of advanced technology component life and cost were generated, since both factors are still to be determined, and a discounted cash flow analysis was conducted to establish a coal production cost. Breakeven and optimal lives and costs for the advanced technology components were found through comparison of coal production costs to that of the baseline cost of coal production. Under reasonable parameter levels of component lives and costs, a 3.5 percent reduction in coal production cost can be achieved.

AN IMPROVED PRESSURE CORING SYSTEM FOR FLUID CONTENT MEASUREMENTS, A. L. McFall, P. A. McGuire, Sandia National Laboratories, SAND79-0856A, Proceedings of Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology, August 22-24, 1979, Tulsa, Oklahoma.

An improved tool for obtaining cores under near in-situ conditions for accurate fluid content measurements will be described. Applications concern the determination of the saturations of tight gas sands and unfractured shales. In addition, oil reservoirs, both new and those in secondary or tertiary recovery stages, will benefit. Three separate areas of system improvement research are discussed: 1) incorporation of a low-invasion fluid that is stored in the core retriever and is extruded to seal and protect the core, 2) the design of a polycrystalline diamond compact bit with features to reduce fluid invasion and increase

penetration rate, and 3) mechanical changes to allow the taking of larger diameter cores with greater reliability. The low-invasion fluid consists of a highly viscous, brine-based polymer system with sized calcium carbonate bridging particles to minimize invasion. This special low-invasion coring fluid has been selected from several candidates that were laboratory tested at simulated downhole conditions. Both static and dynamic filtration characteristics were considered. The coring bit is a high performance design that utilizes an extended pilot section to keep the conventional drilling mud away from the core. Polycrystalline cutters are utilized to yield high penetration rates. Results from the laboratory testing of this bit will be presented. The status of the mechanical system development will also be discussed.

EVALUATION OF HIGH TEMPERATURE LUBRICANTS FOR DOWNHOLE MOTORS IN GEOTHERMAL APPLICATIONS, SAND79-7085C, P. H. DeLafosse, G. A. Tibbitts, and S. J. Green, Terra Tek, Inc., under Sandia Laboratories Contract No. 07-7298, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 149, Reno, Nevada.

A Bearing-Seal Package is being developed for use with downhole motors and turbines for drilling geothermal wells. The lubricant will be sealed in the bearing section which will allow the bearings to operate directly in the lubricant. The development of the Bearing-Seal Package involves the improvement of high temperature seals and lubricants. Candidate high temperature lubricants were tested in the High Temperature Lubricant Tester under elevated temperatures and pressures. A list of candidate high temperature lubricants, a description of the lubricant test program, and the lubricant test results are presented.

B. Advanced Drilling Systems

INVESTIGATIONS INTO THE EFFECTS OF AN ARC DISCHARGE ON A HIGH VELOCITY LIQUID JET, SAND77-1135, Charles F. Huff, Alan L. McFall, Sandia National Laboratories, Proceedings of Energy Technology Conference and Exhibition, ASME, Houston, Texas, September 18-23, 1977.

High velocity liquid jets have been shown to be effective in removing rock in drilling and mining. The high pressures needed to accelerate the fluid to the required velocities are difficult to sustain at reasonable costs. The effect of an arc discharge on the stream of liquid is investigated to determine the value of the spark as an enhancement device. The primary effects investigated are the enhancement of the initial shock wave by the stream velocity, the water hammer from the interrupted stream, the possibility of disruption of the arc by the jet, and the jetting into a collapsing cavitation bubble. All of the experiments are conducted at atmospheric conditions with an analysis of the effects of hydrostatic pressure on the system. The experimental apparatus is a 25 kV capacitive discharge system to develop the arc in a liquid with a jet passing between the electrodes. Pressures up to 20 MPa (3 kpsi) that give velocities of 200 m/s (650 fps) are used in the experiments. The primary diagnostic techniques are piezo-electric pressure transducers, framing and streak cameras, and rock specimen damage observations.

A definite enhancement in the rock removing capabilities is observed. Steady jets that will not erode a specimen become effective in rock erosion when disrupted by an arc discharge. The energy required by the arc discharge is much less than the amount required to comminute rock with the spark alone. Problems in operating an impulse type jet cutter at atmospheric pressure when the working fluid is not degassed are discussed.

EVALUATION OF CAVITATING JETS FOR INCREASED GEOTHERMAL DRILLING RATES, Andrew F. Conn, Hydronautics, Incorporated; Robert P. Radtke, NL/Hycalog, under Contract No. 07-7067 with Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 2, July 1978, p. 113, Hilo, Hawaii.

A program now underway has the ultimate objective of providing improved bit designs for deep-hole drilling, either for geothermal or fossil energy extraction. The bits would incorporate several CAVIJET™ cavitating fluid jet nozzles, in lieu of the conventional nozzles now sometimes used in such bits. Thus, in addition to providing the many tasks now required of the drilling mud, such as cleaning and cooling of the bit face and transporting the rock cutting to the surface, this new concept would exploit the destruction energy of cavitation induced in the mud to help break or weaken the rock.

REPORT OF THE WORKSHOP ON ADVANCED GEOTHERMAL DRILLING AND COMPLETION SYSTEMS, SAND79-1195, Samuel G. Varnado, Sandia National Laboratories, June 1979.

This report summarizes the discussions, conclusions, and recommendations of the Workshop on Advanced Geothermal Drilling and Completion Systems which was held in New Orleans, Louisiana, January 9-11, 1979. The purpose of the workshop was to identify new drilling and completion

systems that have the potential for significantly reducing the cost of geothermal wells, and to provide recommendations to Sandia Laboratories and the Department of Energy as to the research and development tasks that are required to develop these advanced systems. Participants in the workshop included representatives from private industry, universities, and government who were organized into four working groups as follows: Rock Drilling Technology, Surface Technology, Borehole Technology, and Directional Drilling Technology.

ROCK CUTTING WITH CAVITATING JETS UNDER SIMULATED DEEP-HOLE CONDITIONS, Andrew F. Conn, Hydronautics, Incorporated; Robert P. Radtke, NL/Hycalog, under Contract No. 07-7067 with Sandia National Laboratories with cost-sharing by NL/Hycalog, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 121, Reno, Nevada.

The feasibility of adapting the CAVIJET® cavitating fluid jet method for augmenting the performance of deep-hole drilling bits has been demonstrated. Rock cutting tests in a chamber using drilling mud, and with ambient pressures up to 27.6 MPa (4,000 psi), defined the effects of pressure on CAVIJET performance. Enhanced cutting rates to simulated depths of about 1,200 m (4,000 ft) were observed, and no adverse effects were seen when comparing 1.1 to 1.4 gm/cm^3 (9.3 to 12 ppg) mud versus water as the working fluid. Preliminary roller bit laboratory trials indicated that improved rates of penetration can be achieved by substituting CAVIJET nozzles for conventional nozzles.

BOREHOLE DEPTH AND ITS EFFECT ON THE PERFORMANCE OF FLUID JETS, David A. Summers, University of Missouri-Rolla, under contract to Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 693, Reno, Nevada.

The use of high pressure water jets as a means of improving drilling rates has led to varying results, where different companies have carried out the research. This paper, based on research at the University of Missouri-Rolla, explains the reason for the dichotomy in the results and also suggests a means by which the performance of jets on bits, and hence, drilling performance, can be improved.

FACTORS AFFECTING SEAL LIFE IN DOWNHOLE MOTORS, SAND79-7123, D. W. Dareing, Maurer Engineering, Inc., work under Sandia National Laboratories Contract No. 07-7298.

Life expectancy of rotary seals in downhole motors depends both on the temperature generated by sliding friction and on the ambient temperature. A parameter study which led to an improved, temperature-reducing seal configuration is described in this report.

PROGRAM FOR THE IMPROVEMENT OF DOWNHOLE DRILLING-MOTOR BEARINGS AND SEALS, PHASE III, PART 1: FINAL REPORT, SAND79-7124, Terra Tek, Sandia National Laboratories Contract No. 07-7298 Report, January 1980.

This report summarizes a systematic laboratory testing and evaluation program to select high-temperature seals, bearings, and lubricants for geothermal downhole drilling motors.

PROGRAM FOR THE IMPROVEMENT OF DOWNHOLE DRILLING-MOTOR BEARINGS AND SEALS, PHASE III, PART 2: SEMIANNUAL REPORT, SAND79-7125, Terra Tek, Sandia National Laboratories Contract No. 07-7298 Report, January 1980.

This report documents the first six months of a program to improve downhole drilling motor bearings and seals for geothermal applications.

BENDING STRESS AND FREQUENCY CALCULATIONS FOR THE BEARING-PACK SHAFT, SAND80-7030, Jeff Barnwell, Don W. Dareing, Maurer Engineering, Inc., Sandia National Laboratories Contract No. 07-7298 Report, February 1980.

The bearing-pack shaft investigation was conducted to analyze bending and cycle fatigue stresses and resonance. The bending stresses produced were considered to be minimal, and the cycle fatigue stress was less than the material's endurance level. Resonating frequencies were estimated to be sufficiently high to preclude problems.

CONSIDERATIONS IN THE USE OF WATER JETS TO ENLARGE DEEP SUBMERGED CAVITIES, D. A. Summers, Z. Sebastian, University of Missouri-Rolla, under Sandia National Laboratories Contract No. 13-3246, Proceedings of 5th Symposium on Water Jet Cutting Technology, BHRA, Hanover, Germany, June 2-4, 1980.

While the use of geothermal energy is growing, environmental considerations have raised potential economic barriers to its future progress. For example, it is necessary that all the geothermal brine be reinjected underground to stop surface pollution. In the case of the deep geopressured resources of the Texas Gulf, such a move will require that all the heat energy obtained from the water be utilized in reinjecting the geothermal fluid.

In order to facilitate use of reinjection wells, and to lower their cost, it has been proposed that a single well be reamed from 22-1/2 cm to 2 m diameter over an increment of 70 m at a depth of 2000 m. In this manner a single well would be capable of coping with flow rates which currently necessitate a dozen wells being emplaced. The problems encountered in using high pressure water jets for this reaming operation are described. Limiting parameters on the use of high pressure water jets and their operating diameters are identified. The considerable advantages to the use of long chain polymers in such a hostile environment are also delineated.

LABORATORY TESTING OF PERCUSSION DRILLS FOR GEOTHERMAL APPLICATIONS, SAND80-1351C, John T. Finger, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 4, September 1980, p. 289, Salt Lake City, Utah.

This report describes laboratory tests of percussion drilling tools which were done at Drilling Research Lab, Salt Lake City, during February, 1980. The purpose of the tests was threefold: a) to compare the penetration rates of different hammers with each other and with conventional rotary drilling, b) to measure and compare the hammer pulses at normal and high temperatures, and c) to establish hammer life and failure modes at high temperature. Two roller bit hammers and three solid bit hammers were tested. All exhibited much higher rates of

penetration in granite than were obtained with conventional rotary techniques. Tests at high temperature revealed several failure modes for the air driven hammers. Minor modifications should allow operation of these hammers at high temperature.

C. Drilling Fluids

IMPROVED GEOTHERMAL DRILLING FLUIDS, FINAL REPORT, JUNE 1976-JUNE 1977, Larry J. Remont, William J. McDonald, William C. Maurer, William A. Rehm, Maurer Engineering, Inc., Houston, Texas, work done under contract to Sandia National Laboratories and the U. S. Department of Energy.

This study addresses the problems encountered with geothermal drilling fluids. Areas of research considered in this work include the substitution of alternate materials for sodium bentonite, the use of novel filtration control additives, and novel approaches to keeping geothermal muds from solidifying at high temperatures. A mud formulation which was developed in this study is recommended.

PORTABLE HIGH-TEMPERATURE, HIGH-PRESSURE VISCOMETER DEVELOPMENT, SAND78-1409, Robert C. Reineke, Sandia National Laboratories, March 1979.

A field instrument for measuring the rheological characteristics of drilling mud at temperatures up to 500°F (260°C) and pressures of 12,500 psi has been developed. This instrument allows a direct determination of fluid viscosity under simulated downhole conditions. The instrument is comprised of a rotational viscometer packaged in a high-temperature, high-pressure vessel. Heat is applied by use of electric resistance heaters, and pressure is applied by a hand-operated hydraulic pump. The unit is completely portable and weighs approximately 60 pounds. The instrument has been utilized to measure the properties of both water-based and oil-based drilling fluids to temperatures of 260°C.

This report describes the design and construction of the instrument and presents the results of measurements of six different drilling fluid formulations. These test results show that in general, water-based samples exhibit a marked increase in viscosity with increasing temperature, but little effect is observed with increasing pressures. In oil-based muds the thinning effect caused by increasing temperature is partially compensated for by the thickening effect of increasing pressure.

WORKSHOP ON GEOTHERMAL DRILLING FLUIDS, SAND79-7120, held by Maurer Engineering, Inc., Houston, Texas, May 23, 1978, under contract to Sandia National Laboratories.

This report contains eight papers relating to the development of geothermal drilling fluids.

THE CONSTRUCTION AND EVALUATION OF AN IMPROVED PRESSURE CORING SYSTEM, SAND79-1051C, A. L. McFall, Sandia National Laboratories, Proceedings of Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology, Tulsa, Oklahoma, August 22-24, 1979.

An improved pressure coring system is necessary for the accurate determination of the true fluid content of oil and gas reservoirs. This is particularly important in those fields being planned for secondary or tertiary recovery programs. Two major areas for improvement have been considered; bit design and coring fluids. Specialized bits have been designed and fabricated to achieve high penetration rates and to reduce

the contact of wellbore fluids with the core. Water based coring fluids containing polymers and selected bridging particles have been laboratory tested, under simulated downhole conditions, to effect reduced core washing. These fluids are intended to be stored in the core retriever to lubricate and cool the portion of the bit that is in contact with the core. Presently, these two features are being incorporated into an existing pressure coring system, and upcoming field test plans will be discussed.

AN INVESTIGATION OF LOW INVASION FLUIDS FOR PRESSURE CORING, SAND79-1052, P. L. McGuire, A. L. McFall, Sandia National Laboratories, Proceedings of Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology, Tulsa, Oklahoma, August 22-24, 1979.

A new pressure coring system is being developed which could significantly improve the measurement of in-situ oil and gas saturations in hydrocarbon reservoirs. This improved system will incorporate a low-invasion fluid that is stored in the core retriever and is extruded to seal and protect the core. The low-invasion fluid consists of an extremely viscous, brine-based polymer stem with sized calcium carbonate bridging particles to minimize invasion. This special coring fluid has been selected from several candidates that were laboratory tested at simulated downhole conditions. Both static and dynamic filtration characteristics were considered. Other important properties of this low-invasion pressure coring fluid are also discussed, including freezing point, formation damage, clay stabilization, wettability changes, and pressure buildup in the core barrel.

NITROGEN GENERATION METHODS TO BE USED IN GEOTHERMAL DRILLING, SAND79-1893C, N. J. Norem, J. H. Barnette, B. T. Kenna, Sandia National Laboratories, Proceedings of Workshop on Geothermal Drilling Fluids, held by Maurer Engineering, Inc., Houston, Texas, October 9, 1979.

A major contributor to the high costs associated with geothermal wells is the extensive corrosion of the drill pipe by oxygen present in the drilling fluid. The importance of controlling the corrosive attack of oxygen in the drilling operation is evident when the cost and availability of drill pipe is considered. A possible method for reducing the corrosive attack of oxygen is the utilization of an inert drilling fluid such as nitrogen. Nitrogen could replace air in foam drilling, air drilling, and for the aeration of drilling muds. The major problem with using nitrogen is producing a sufficient quantity of it with a purity of less than 5 ppm of oxygen at the drilling site. This paper looks into the feasibility of using this method.

FIELD TRIAL OF HTM-1, SAND79-7090C, L. Remont, Maurer Engineering, Inc., Proceedings of Workshop on Geothermal Drilling Fluids, held by Maurer Engineering, Inc., Houston, Texas, October 9, 1979, under contract to Sandia National Laboratories.

Work completed in 1977 identified the following mud-related problems which are encountered in geothermal drilling: mud solidification, lost circulation, and corrosion. Research sponsored by the DOE showed that mud solidification is related to the accumulation of bentonite from drilled solids as well as from additions of drilling mud bentonite.

Mud solidification is aggravated by the thermal decomposition of thinners at temperatures encountered in geothermal drilling. Loss of mud is caused by low formation pressures, fractured reservoirs and pressure surges caused by high-temperature mud gelation. Rapid corrosion rates are experienced in geothermal drilling operations because of the high temperatures encountered, the intrusions of salt formation fluids, the decomposition of thinners into acidic by-products, the influx of hydrogen sulfide and carbon dioxide, and the erosional effects when air is used as a drilling fluid.

HIGH TEMPERATURE CLAY CHEMISTRY, SAND79-7091C, N. Guven and L. Carney, Texas Tech University, Proceedings of Workshop on Geothermal Drilling Fluids, held by Maurer Engineering, Inc., Houston, Texas, October 9, 1979.

Clay minerals in the drilling fluids may undergo chemical and structural changes under increased temperatures and presssures, and in complex chemical environment of geothermal wells. Understanding of these changes is necessary in order to design appropriate clay-based fluids for drilling geothermal wells. For this purpose hydrothermal experiments were conducted with the clays such as sepiolite, attapulgite, saponite and bentonite. The rheological and mineralogical changes were followed in the clays subjected to hydrothermal treatments with and without the addition of the salts and the hydroxides of Na, K, Ca, and Mg.

EVALUATION OF GEOTHERMAL FOAMS, SAND79-7092C, G. Matula, Maurer Engineering, Inc., Proceedings of Workshop on Geothermal Drilling Fluids, held by Maurer Engineering, Inc., Houston, Texas, October 9, 1979.

Problems resulting from inadequate drilling fluids are the most frequently quoted reasons for high geothermal drilling costs. Severe corrosion and erosion problems are common when air drilling; yet slow drilling rates, poor filtration control, loss of circulation, and mud gelation often occur when using muds. In order to ascertain how drilling foams might be utilized in geothermal drilling to solve some of these problems (hence reducing geothermal well costs) Sandia Laboratories contracted with Maurer Engineering to evaluate drilling foams for geothermal applications and to recommend a program for developing geothermal drilling foams.

PERFORMANCE CHARACTERISTICS OF GEOTHERMAL MUDS AT TEMPERATURE AND PRESSURE, SAND79-7094A, Dr. Edward Blick, University of Oklahoma, Proceedings of Workshop on Geothermal Drilling Fluids, held by Maurer Engineering, Inc., Houston, Texas, October 9, 1979.

Drilling mud tests were completed on Baroid and Mudtech drilling muds. These muds were tested on the University of Oklahoma Flow Loop. This loop has the capacity for testing drilling muds at pressures and temperatures up to 2,000 psia and 500°F. The two drilling muds were pumped through the loop for several hours under simultaneous high shearing and high heating conditions. The fluids were heated in one portion of the loop and cooled in another portion. Records were noted on the temperature and flow times at which each fluid became unstable.

AQUEOUS FOAMS FOR GEOTHERMAL DRILLING FLUIDS I. SURFACTANT SCREENING, Peter B. Rand, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 565, Reno, Nevada.

Aqueous foam is a promising drilling fluid for geothermal wells because it will not harm the producing formation and would eliminate the erosion problems of air drilling. Successful use of aqueous foam will require a high foaming surfactant which will: 1) be chemically stable in the harsh thermal and chemical environment, and 2) form stable foams at high temperatures and pressures. This paper presents the procedures developed to generate and test aqueous foams and the effects of a 260°C temperature cycle on aqueous surfactant solutions. More than fifty selected surfactants were evaluated, with representatives from the amphoteric, anionic, cationic, and nonionic classes included. Most surfactants were severely degraded by this temperature cycle; however, some showed excellent retention of their properties. The most promising surfactant types were the alkyl and alkyl aryl sulfonates and the ethoxylated nonionics.

WORKSHOP ON GEOTHERMAL DRILLING FLUIDS, SAND79-7117, Maurer Engineering, Inc., October 9, 1979, Houston, Texas, under contract to Sandia National Laboratories.

Thirteen papers relating to the development of geothermal drillings fluids are presented.

SURVEY FOR GEOTHERMAL COMPLETION FLUIDS, SAND79-7121, Michael R. Childers, Brinadd Company, Inc., Sandia National Laboratories Contract No. 13-0370 Report, January 1980.

A survey of oil field fluids companies indicates that there are no geothermal completion fluids on the market. It is recommended that development of a completion fluid and appropriate support testing be funded.

DEVELOPMENT OF DRILLING FOAMS FOR GEOTHERMAL APPLICATIONS, SAND79-7122, William J. McDonald, Larry J. Remont, William A. Rehm, Maurer Engineering, Inc., and Martin E. Chenevert, Chenevert and Associates, Sandia National Laboratories Contract No. 07-7068 Report, January 1980.

This report, prepared at the request and under contract to Sandia Laboratories, addresses the use of foam drilling fluids in geothermal applications. The initial three chapters provide a description of foams -- what they are, how they are used, their properties, equipment required to use them, the advantages and disadvantages of foams, etc.

Geothermal applications are discussed. Results of industry interviews presented indicate significant potential for foams, but also indicate significant technical problems to be solved to achieve this potential. Testing procedures and results of tests on representative foams provide a basis for work to develop high-temperature foams. A seven-year directed effort to develop the needed materials and equipment is presented.

GEOTHERMAL DRILL PIPE CORROSION TEST PLAN, SAND80-1090, Billy C, Caskey, and K. S. Copass, Sandia National Laboratories.

Plans are presented for conducting a field test of drill pipe corrosion, comparing air and nitrogen as drilling fluids. This test will provide data for evaluating the potential of reducing geothermal well drilling costs by extending drill pipe life and reducing corrosion control costs. Union Geothermal Company of New Mexico, a subsidiary of Union Oil Company of California, is participating by providing the drill rig, the well, and other support. Sandia National Laboratories is providing the nitrogen, recording the data, and assessing the results. The ten-day test will take place during Fall, 1980, at the Baca Location in Sandoval County, New Mexico.

LOW INVASION FLUIDS FOR PRESSURE CORING, SAND80-2561, A. A. Heckes, A. L. McFall, and S. M. Delgado, Sandia National Laboratories.

A program has been completed to develop improved low invasion fluids for pressure coring applications. This paper describes the results of an experimental investigation which was performed on seven different low invasion fluids. The investigation employed commercially available calcium carbonate ($CaCO_3$) materials which were compared using two different sandstone core samples (brown and gray berea) and two simulated field conditions (static and dynamic).

The results indicate that the presently used mixture of 10 lb/bbl HEC polymer and 300 lb/bbl $CaCO_3$ in a $CaCl_2$ eutectic brine mixture appears to be a good choice for minimizing invasion of the core sample. Minor improvements in core invasion are achieved by matching the $CaCO_3$ particle size to the formation pore size. Experimentation or prior experience are necessary for choosing the type of $CaCO_3$ to be used. At best, the invasion of the core may only be slowed and not stopped completely. Factors which cause relatively large amounts of filtrate intrusion into the core are long exposure times, low fluid viscosities, and low solids content of the fluid. Curves demonstrating the effectiveness of high polymer and $CaCO_3$ particle concentrations and comparing the core invasion of water, bentonite drilling mud and the seven low invasion fluids are presented.

DRILLING FLUID/FORMATION INTERACTION AT SIMULATED IN SITU GEOTHERMAL CONDITIONS: FINAL REPORT, SAND80-7058, D. O. Enniss, J. L. Bergosh, S. W. Butters, A. H. Jones, Terra Tek, Inc., under Sandia National Laboratories Contract No. 13-9407.

Interaction of drilling fluids with a geothermal reservoir formation can result in significant permeability impairment and therefore reduced well productivity. This interaction is studied under simulated in situ geothermal conditions of overburden stress, pore fluid pressure, temperature, and pore fluid chemistry. Permeability impairment of an East Mesa KGRA reservoir material is evaluated as a function of stagnation time, drilling fluid, and temperature. Results indicate that all of these parameters contribute significantly to the magnitude and the reversibility of the impairment.

DRILLING FLUID/FORMATION INTERACTION AT SIMULATED IN SITU GEOTHERMAL CONDITIONS, D. O. Enniss, J. L. Bergosh, S. W. Butters, A. H. Jones, Terra Tek, Inc., under Sandia National Laboratories Contract No. 13-9407, Transactions of Geothermal Resources Council Annual Meeting, Vol. 4, September 1980, p. 285, Salt Lake City, Utah.

Abstract same as report above.

D. Materials

FATIGUE OF STEEL IN SIMULATED DRILLING ENVIRONMENTS, SAND78-0530, K. H. Eckelmeyer, Sandia National Laboratories.

The current guidelines for selection of steel for use as drill stem in H_2S containing environments are based on data obtained in static load tests. In actual use, however, drill stem is frequently subjected to cyclic, or fatigue, loading. This study shows that fatigue loading in a standard H_2S containing testing environment causes crack growth to occur at stress intensities far below the static load threshold. It also shows that material performance rankings based on static load tests are not necessarily meaningful for the more severe case of fatigue loading. It is concluded that the current guidelines could be improved by giving additional consideration to the performances of materials under fatigue loading conditions.

IMPROVEMENTS IN ROTARY SEALS FOR DOWNHOLE MOTORS IN GEOTHERMAL APPLICATIONS, SAND79-7084C, J. G. Wilson, G. A. Tibbitts, A. D. Black, Terra Tek, Inc., under Sandia National Laboratories Contract No. 07-7298, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 785, Reno, Nevada.

The major limitation of downhole mud motors for geothermal well drilling as well as straight-hole and oil well drilling is the bearing section. Reduced bearing life has been a direct result of the inability to seal lubricant in the bearing section. A reliable rotary seal is needed to extend bearing life and to allow high pressure drops across the drill bit for improved bottomhole cleaning and increased drilling rate. The endurance of "high temperature" rotary seal candidates is being measured in a full-scale laboratory seal tester capable of simulating the pressures and temperatures of geothermal well drilling. A description of the currently most successful "high temperature" seals and seal test results and findings are presented.

MATERIALS AND SEAL SYSTEMS FOR THE IMPROVEMENT OF UNSEALED AND SEALED GEOTHERMAL ROCK BITS, SAND80-7136, R. R. Hendrickson, R. W. Winzenried, A. H. Jones, Terra Tek, Inc., under Sandia National Laboratories Contract No. 13-2313.

This research was sponsored by Sandia Laboratories and the U. S. Department of Energy to facilitate the upgrading of conventional unsealed and sealed roller-cone rock bits for geothermal service. Experimental and conventional unsealed bits were subjected to laboratory drilling tests at 250°C (482°F). Bearing life was extended 50% for the experimental bits. Seals and lubricants were developed specifically for sealed, journal-type rock bits. These were evaluated in specifically constructed seal and lubricant test machines. Results indicate the elastomeric seals are capable of 200°C (392°F) service. Three mechanical seal systems were built and evaluated. Three lubricants demonstrated 316°C (600°F) capability. Development is continuing on elastomeric seals, mechanical seals, and lubricants. Detailed descriptions of previous work, and the unique test equipment are presented.

E. Completion Technology

STATE-OF-THE-ART IN WELL COMPLETION TECHNOLOGY AS APPLIED TO GEOTHERMAL DEVELOPMENT, SAND78-7008, R. M. Jorda, with contributions from R. C. Ellis, Completion Technology Company, Sandia National Laboratories Contract No. 05-6199, May 1978.

In June, 1977, a request was made by Sandia Laboratories for a state-of-the-art report concerning well completions for geopressured and geothermal energy source and injection wells. This preliminary report covers 1) corrosion and metal problems, 2) scale deposition and control, 3) general production interval completion techniques, and 4) a model of an all-liquid heat recovery system. Both hot water geopressured source wells and water disposal (injection) wells are discussed in some detail. Areas for further development and study with regards to United States Gulf Coast geopressured well completions are identified. Maximum conditions for the hot water geopressured source wells are as follows: vertical well depth - 20,000 ft (6096 meters), temperature - 500°F (260°C), and bottomhole pressure - 15,000 psi (1034 bars). The report contains some data on corrosion and scale which extends to higher temperatures.

AN ENGINEERING STUDY OF WATER REINJECTION FOR GEOTHERMAL SYSTEMS, SAND78-7009, R. M. Jorda, Completion Technology Company, Sandia National Laboratories Contract No. 05-6199 report, January 1978.

The technology of water reinjection is quite broad, and traverses many subsets of physics, chemistry and applied engineering. Ample knowledge is available to assure that most of the problems associated with subsurface injection of liquids can be solved at costs which should not be excessive, and with parasitic power requirements which are not expected to be inordinate. The large number of existing liquid injection systems in oil and other industries, many of which have been operating three decades, provide some guidance in this type of operation.

This report contains information related to the effects of suspended solids and, to some extent, vapor bubbles on injection well performance. The means of evaluating the tolerable amounts of solids in injected water are presented, and all necessary derivations, equations, test procedures, and correlations are explicitly described.

AN ANALYSIS OF WATER REINJECTION AT THE NILAND GEOTHERMAL TEST SITE, SAND78-7060, R. M. Jorda, Completion Technology Company, with contributions by Leonard E. Baker, Sandia National Laboratories; Mark Voss and David C. Williams, Champion Chemicals, Inc.; Sandia National Laboratories Contract Report No. 05-6199, May 1978.

The problems associated with reinjecting spent geothermal brines are currently under investigation. This effort has included field tests of injection water to evaluate treating equipment effectiveness at the Niland Geothermal Test Loop. Using Champion Chemical, Inc., personnel and equipment under the direction of Sandia and CTC personnel, membrane filter tests were conducted on fluids from the settling tanks, from the test loop, from the clarifier and at the injection well head (Magmamax #3). From this and other information concerning the injection interval, pressure, temperature and well history, an attempt to

predict a well half life was made. The restuls of these calculations were not in agreement with observed well performance. An attempt with some apparent success has been made to understand the possible source of these discrepancies. The cyclic nature of the injection history dictated by need for descaling the test loop, followed by apparent partial recovery of injection acceptance, has led to a theory that is under investigation concerning effect of reheating the injection fluid containing amorphous particulate silica by the reservoir rock and fluid during well shut-in. Preliminary tests indicate some of this finely divided silica may be redissolving with consequent reduction in reservoir damage, and that two widely spaced injection wells in an alternating mode may provide low-cost, long-life injection capacity at Niland and similar geothermal projects.

A MATHEMATICAL MODEL OF DAMAGE COLLARS IN WATER REINJECTION WELLS, SAND78-7063, R. M. Jorda, Completion Technology Company, Sandia National Laboratories Contract No. 05-6199 Report, May 1978.

A recent study of the Imperial Magma-San Diego Gas and Electric Geothermal Experimental Site near Niland, California, suggests that damage collar formation caused by deep invasion of water-borne particulates into the reinjection reservoir may be an important mechanism in water reinjection well performance. A model of damage collar effects has been developed and appears to provide insight which is consistent with information provided by other sources. For effective reinjection system analysis where damage collars are thought to exist, a more explicit understanding of the movement of water-borne particulates through porous media needs to be developed.

USE OF DATA OBTAINED FROM CORE TESTS IN THE DESIGN AND OPERATION OF SPENT BRINE INJECTION WELLS IN GEOPRESSURED OR GEOTHERMAL SYSTEMS, SAND80-7047, Robert M. Jorda, Completion Technology Company, Sandia National Laboratories Contract No. 13-8726 Report, March 1980.

Extremely large volumes of water will have to be reinjected in conjunction with large-scale, future geopressured or geothermal projects. However, cost of drilling and operating injection wells is totally parasitic, in that no income is produced directly by these wells, and some of the energy produced by power plants must be used for injection power. Thus, accurately engineered reinjection systems are critically needed to make proposed geopressured and geothermal developments economically viable. This report is a review of the effects of formation characteristics on injection well performance. Use of data acquired from cores taken from injection horizons to predict injectivity is described. Methods for utilizing data from bench scale testing of brine and core samples to optimize injection well design are presented.

CASING FAILURE MODES IN GEOTHERMAL WELLS, Robert E. Snyder, Completion Technology Company, under contract 13-2297 with Sandia National Laboratories, Transactions of Geothermal Resources Council, Vol. 3, September 1979, p. 667, Reno, Nevada.

Effects of heat, the 100% aqueous environment and a variety of drilling and cementing problems make geothermal well casing design, installation and maintenance significantly different than for oil and gas wells of

similar depths. This review presents common problems that operators have experienced with tubulars that are otherwise properly designed for basic tension, burst and collapse conditions.

PREDICTING INJECTOR PERFORMANCE AT THE PROPOSED MAGMA-SDG&E FIFTY MEGAWATT GEOTHERMAL POWER PLANT, SAND79-7128, Robert M. Jorda, Completion Technology Company, Sandia National Laboratories Contract No. 13-2297 Report.

The spent brine treating facility at the Magma Power-San Diego Gas and Electric Company proposed fifty megawatt geothermal power plant in the Niland KGRA is under construction. The spent geothermal brine will be treated in a sludge-bed clarifier, followed by filtration through rapid mixed-media filters for suspended solids removal.

The injection water treating system and the reinjection well are scheduled to be ready for testing for late spring, 1979. The question of the injection test duration necessary to provide an assessment of the well's long-term injection capability has been raised. This report provides some insight to this question, and includes an advanced method for assessing changes in injection well receptivity, the Injection Performance Map (IPM). The report also contains data which suggest that three to four months of continuous operation with properly treated injection water may be sufficient to forecast the well's long-term injection potential.

A PERFORMANCE EVALUATION OF MAGMA POWER COMPANY'S REINJECTION WELL #46-7 AT THE EAST MESA KGRA, CALIFORNIA, SAND79-7127, Robert M. Jorda, Completion Technology Company, Sandia National Laboratories Contract Report No. 13-0336, January 1980.

The performance of the Magma Power Company's reinjection well #46-7 at East Mesa has been examined. Water was cooled to 100°F ($\pm$) to simulate total heat extraction and then tested using membrane filter flow procedures. The cooled water contains particles which are in the high colloid size range, and formation impairment by these particles is unlikely. There is evidence that acid soluble corrosion products and calcium compounds constitute about two-thirds of the particulates, and that the acid insoluble residue contains precipitated silica, insoluble corrosion products, and possibly formation fines carried in the produced water. Under stabilized conditions, the suspended solids content of the water is less than 2 parts per million. However, during the frequent production well startups, a higher concentration of suspended solids is carried in the produced water and into the injection well, conceivably augmenting fill in the injector. But most likely, fill occurs when the injection well surges during shut-downs, because of inadequate sand control in the well completion.

GEOTHERMAL WELL COMPLETIONS: STATE OF THE ART, Robert E. Snyder, Completion Technology Company, under Sandia National Laboratories Contract No. 05-6119, Geothermal Resources Council Annual Meeting Transactions, Vol. 2, p. 601, July 1978, Hilo, Hawaii.

Present methods for completing steam and liquid dominated, dry rock, and geopressured geothermal wells are described by interpretive review

of actual and proposed operations in The Geysers, Imperial Valley, the Valles Caldera, New Mexico project, and Louisiana-Texas geopressured zones. Limitations of technology and equipment that has been adapted from the petroleum industry to meet new and unique requirements of these downhole environments are objectively analyzed.

F. Supporting Technology

A SIMULATOR FOR SENSITIVITY ANALYSIS OF GEOTHERMAL WELL COST--PROGRESS REPORT, Joseph Polito, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 2, July 1978, p. 537, Hilo, Hawaii.

A computer based simulator for geothermal well costs is being developed by Sandia Laboratories. The purpose of the project is to provide an analysis tool with which to investigate the sensitivity of geothermal drilling costs to various technological improvements. Output from the simulator will provide information to aid the research manager in the allocation of resources to research projects. In its final form the simulator will accept models of rotary and novel drilling systems at the level of aggregation specified by the user. This paper presents an overview and progress report on the development of the simulator.

THE EFFECTS OF CORROSION AND SCALE DEPOSITS ON THE CAPACITY OF WATER REINJECTION WELLS IN LIQUID DOMINATED GEOTHERMAL SYSTEMS, R. M. Jorda, Completion Technology Company, under Sandia National Laboratories Contract No. 05-6199, Transactions of Geothermal Resources Council Annual Meeting, Vol. 2, July 1978, p. 341, Hilo, Hawaii.

Scale deposits or corrosion damage in water reinjection well tubing strings can result in reduction of reinjection capacity, thereby limiting power recovery in liquid dominated geothermal systems. Simulation of a Texas Gulf Coast reinjection well under scaling and corrosive conditions indicates that either scale deposits or corrosion may require a tubing size of at least one nominal diameter larger than would be required if corrosion or scale deposition did not occur. This, in turn, would require the use of larger protective casing strings and bigger drilling bits.

AN IMPROVED PRESSURE CORING SYSTEM FOR FLUID CONTENT MEASUREMENTS, SAND79-0723A, A. L. McFall, Sandia National Laboratories, Proceedings of 54th Annual Technical Conference and Exhibition, Society of Petroleum Engineers of AIME, September 23-26, 1979, Las Vegas, Nevada.

An improved tool for obtaining cores under near in-situ conditions for accurate fluid content measurements will be described. Applications concern the determination of the saturations of tight gas sands and unfractured shales. In addition, oil reservoirs, both new and those in secondary or tertiary recovery stages, will benefit. Three separate areas of system improvement research are discussed: 1) incorporation of a low-invasion fluid that is stored in the core retriever and is extruded to seal and protect the core, 2) the design of a diamond bit with features to reduce fluid invasion and increase penetration rate, and 3) mechanical changes to allow the taking of larger diameter cores with greater reliability. The special low-invasion coring fluid has been selected from several candidates that were laboratory tested at simulated downhole conditions. Both static and dynamic filtration characteristics were considered. The coring bit is a high performance design that utilizes an extended pilot section to keep the conventional drilling mud away from the core. Results from the laboratory testing of this bit will be presented. The status of the mechanical system development will also be discussed.

COMPUTING DOWNHOLE TEMPERATURE IN PETROLEUM AND GEOTHERMAL WELLS, Gary R. Wooley, under contract to Sandia National Laboratories, SPE Paper No. 8441, SPE 54th Annual Technical Conference and Exhibition, Las Vegas, Nevada, September 26, 1979.

Downhole temperatures are an important part of the drilling and completion of any well. For unusual environments, such as in geothermal, arctic, or deep hot wells, downhole temperatures are more difficult to define and are more important for design of a well. A better understanding of downhole temperatures can improve well designs by aiding in casing design, cement and drilling fluid formulation, packer selection and many other applications. A computer model has been developed to determine downhole wellbore and earth temperatures. Temperatures are computed in flowing or shut-in fluid streams, in the well outside the flowing stream and in the formation. Flowing options available in the model include: injection/production, forward/reverse circulation, and drilling. A special feature for circulation and drilling is simultaneous fluid loss or production. Model predictions are compared to an exact solution and to field temperature data collected from petroleum and geothermal wells. Good agreement has been achieved with the comparisons. Sensitivity studies define the importance of inlet temperature, flow rate, and depth on downhole temperatures during production and during forward circulation. Transient bottomhole temperatures for circulation and surface temperatures for production are provided for two values of each variable. Also, the steady temperature profiles are provided for the same two values. Results show that each of these three variables has a strong influence on downhole temperatures.

A SIMULATOR FOR SENSITIVITY ANALYSIS OF GEOTHERMAL WELL COST--RECENT RESULTS, Joseph Polito, Sandia National Laboratories, and David M. Smith, The BDM Corporation, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 545, Reno, Nevada.

A computer based simulator for geothermal drilling has been developed at Sandia Laboratories to assess the value of new geothermal drilling technology. This paper presents the results of an analysis of diamond compact drill bits when applied to drilling in three geothermal areas: The Geysers, CA; Cove Fort-Sulphurdale, UT, and the Baca location in New Mexico. The parameters of rate of penetration, bit cost, and bit life were examined to determine the performance required for cost reductions to be achieved. The analysis indicates that substantial savings may be realized when long bit runs are possible. Technology which will reduce the cost and time of frequent drilling contengencies and/or reduce bit cost will make high performance bits more attractive.

WELLBORE AND SOIL THERMAL SIMULATION FOR GEOTHERMAL WELLS: COMPARISON OF GEOTEMP PREDICTIONS TO FIELD DATA AND EVALUATION OF FLOW VARIABLES, PART II REPORT, SAND79-7116, Gary R. Wooley, Enertech Engineering and Research Co., Sandia National Laboratories Contract No. 13-0212 Report, January 1980.

A better understanding of downhole temperatures in a geothermal well will improve many aspects of well design. This report presents the results of testing and application of the computer code GEOTEMP, which predicts these downhole temperatures.

USER'S MANUAL FOR GEOTEMP, A COMPUTER CODE FOR PREDICTING DOWNHOLE WELLBORE AND SOIL TEMPERATURES IN GEOTHERMAL WELLS, APPENDIX TO PART I REPORT, SAND79-7118, Gary R. Wooley, Enertech Engineering and Research Company, Sandia National Laboratories Contract No. 13-0212 Report, January 1980.

GEOTEMP is a computer code that calculates downhole temperatures in and surrounding well. Temperatures are computed as a function of time in a flowing stream, in the wellbore, and in the soil. Flowing options available in the model include the following: 1) injection/production, 2) forward/reverse circulation, and 3) drilling. A special feature for Options 2 and 3 is an added secondary production that joins the circulating fluid. This manual describes how to input data to the code and what results are printed out, provides six examples of both input and output, and supplies a listing of the code. The user's manual is an appendix to the Part I report, "Development of Computer Code and Acquisition of Field Temperature Data," for Sandia Contract No. 13-0212. Although GEOTEMP is designed for applications to geothermal wells, it is a valuable tool for all wells. A few examples are presented, but almost unlimited combinations of well descriptions, casing programs, temperature distributions and fluid types are possible. Flowing options allow accurate modeling of drilling and completion of a well, workovers, injection or production, and even shut-in during or after the life of a well. Furthermore, all these capabilities can be expanded for special applications by adjusting thermal properties or well dimensions, and by making rather simple modifications to the computer code. However, to encourage extensive application of GEOTEMP, input data has been minimized to information commonly available for all wells.

WELLBORE AND SOIL THERMAL SIMULATION FOR GEOTHERMAL WELLS: DEVELOPMENT OF COMPUTER MODEL AND ACQUISITION OF FIELD TEMPERATURE DATA, PART I REPORT, SAND79-7119, Gary R. Wooley, Enertech Engineering and Research Company, Sandia National Laboratories Contract No. 13-0212 Report, January 1980.

A downhole thermal simulator has been developed to improve understanding of the high downhole temperatures that affect many design factors in geothermal wells. This report documents this development and presents field temperature data for flowing and shut-in conditions.

SEAL/LUBRICANT SYSTEMS FOR GEOTHERMAL DRILLING EQUIPMENT, SAND80-7101, R. R. Hendrickson, R. W. Winzenried, Terra Tek, Inc., Sandia National Laboratories Contract No. 13-8783.

This report describes the development and testing of seals and lubricants for journal-type roller-cone rock bits for drilling into geothermal reservoirs at temperatures over 260°C (500°F). The conditions experienced by seals and lubricants subjected to geothermal drilling are reviewed along with the basic design requirements for roller-cone bit seals and journal bearing lubricants. Two unique test facilities are described: a seal test machine which simulates pressures, temperatures, and mechanical eccentricities, and a lubricant tester capable of evaluating load-bearing ability at temperature and pressure. Three candidate elastomeric compounds demonstrated 288°C (550°F) capability and several others demonstrated 260°C (500°F) or greater capability. Successful elastomeric seal candidates were proprietary compounds

based on EPD, Kalrez, and/or Viton polymers. Three mechanical seals for reservoir temperatures over 288°C (550°F) are presented. Lubricant screening tests on more than 50 products are summarized, and several newly developed lubricants which meet both the compatiblity and lubrication requirements are described.

Several seal/lubricant systems are recommended for laboratory or field geothermal drilling tests in roller-cone drill bits. The future availability of drill bits for geothermal use is duscussed, as well as the potential spin-offs of the program findings for non-geothermal roller-cone bits.

GEOTHERMAL WELL COST SENSITIVITY ANALYSIS: CURRENT STATUS, C. C. Carson and Y. T. Lin, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 4, September 1980, p. 277, Salt Lake City, Utah.

The geothermal well-cost model developed by Sandia National Laboratories is being used to analyze the sensitivity of well costs to improvements in geothermal drilling technology. This paper discusses three interim results from this modeling effort: the sensitivity of well costs to bit parameters, rig parameters, and material costs; an analysis of the cost reduction potential of an advanced bit; and a consideration of breakeven costs for new cementing technology. All three results illustrate that the well-cost savings arising from any new technology will be highly site-dependent but that in specific wells the advances considered can result in significant cost reductions.

DEVELOPMENT AND TESTING OF SEALS AND LUBRICANTS FOR GEOTHERMAL ROCK BITS, R. R. Hendrickson and R. W. Winzenried, Terra Tek, Incorporated, under contract to Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 4, September 1980, p. 293, Salt Lake City, Utah.

The paper describes the successful development and evaluation of seals and lubricants for journal-type rock bits for use in geothermal reservoirs. Elastomeric compounds which sealed effectively to temperatures of 288°C (550°F), and mechanical seals for reservoir temperatures over 288°C (550°F) are presented. Newly developed lubricants which meet both the compatibility and lubrication requirements are described. Several seals and lubricants are recommended for high temperature laboratory drilling and field geothermal drilling tests in roller-cone bits.

COST UNCERTAINTY AND SIMPLE MODELING FOR DIRECT USE GEOTHERMAL RESOURCES, Stephen E. Schoderbek, Dennis J. Anderson, Jean M. Miewald, The BDM Corporation, under contract to Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 4, September 1980, p. 743.

Detailed sensitivity analysis of a direct heat application produces an area of cost uncertainty which is significantly large when reasonable values of reservoir characteristics are modeled. Principal cost drivers are identified and their interaction examined through regression analysis. A simple equation with first and second order

effects is generated and explains 99% of the variance among cost estimates. A simple nomograph is developed with three cost drivers to aid in reaching minimum cost decisions.

COMPUTING DOWNHOLE TEMPERATURES IN CIRCULATION, INJECTION AND PRODUCTION WELLS, Gary R. Wooley, Enertech Engineering and Research Co., under contract to Sandia National Laboratories, Journal of Petroleum Technology, September 1980, p. 1509.

A computer model is presented for predicting downhole wellbore temperatures in flowing or shut-in fluid streams, in casing and cement, and in formations. Flowing options include injection/production, forward/reverse circulation, and drilling. Model predictions agree with field temperature data. The influences of temperature, flow rate, and depth on downhole temperatures are presented.

ECONOMIC ANALYSIS OF ROOF DRILL BITS AND CONTINUOUS MINER PICKS, SAND80-7059, Leonard L. Felts, David P. Gabello, Fred P. Hayoz, TRW Energy Systems Planning Division, under Sandia National Laboratories Contract No. 13-8714.

The economic impact of substituting long life cutters for the tungsten carbide cutters presently used on roof bolt drill bits and continuous miner picks in underground coal mines has been analyzed. The analysis considers two room and pillar mines using continuous miners and twin boom roof bolters and one mine that employs an advanced miner-bolter extraction system. For each of these base cases, equipment lists, capitalization costs, and operating labor requirements are considered to determine mine performance in terms of cost of coal produced. Increased penetration rate was found to be of secondary importance compared to increased bit or pick life. Results are given that show tool life and tool cost required to achieve parity with tungsten carbide tools and percent savings when the long life tools exceed the parity. For example, a decrease in production costs of up to 8% is projected for mines using continuous miners and advanced technology roof bits with a 300' life.

G. Program Reviews/Summaries

GEOTHERMAL WELL TECHNOLOGY DRILLING AND COMPLETION PROGRAM PLAN, SAND77-1630, M. M. Newsom, J. H. Barnette, L. E. Baker, S. G. Varnado, and J. Polito, Sandia National Laboratories, March 1978.

The drilling and completion portion of the long-range Geothermal Well Technology Program is presented. A nine-year program is outlined based upon an objective of reducing the cost of geothermal energy development and providing a major stimulus to meeting the power-on-line goals established by the Department of Energy. Major technological challenges to be addressed in this program include improvements in geothermal drilling fluids, downhole drilling motors, rock bits and the development of high flow rate, high temperature completion and reinjection techniques. In addition, fundamental studies will be conducted in drilling energetics to improve the understanding of drilling mechanics. This will lead to advance development of high performance, low cost geothermal drilling systems. This program plan has been prepared for the Division of Geothermal Energy of the Department of Energy.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT, SAND78-0670C, S. G. Varnado and H. M. Stoller, Sandia National Laboratories, Transactions of Geothermal Resources Council, Vol. 2, July 1978, p. 675, Hilo, Hawaii.

The high cost of drilling and completing geothermal wells is an impediment to the development of geothermal energy resources. Technological deficiencies in rotary drilling techniques are evidenced when drilling geothermal wells. The Division of Geothermal Energy (DGE) of the U. S. Department of Energy has initiated a program aimed at developing new drilling and completion techniques for geothermal wells. The goals of this program are to reduce well costs by 25% by 1982 and by 50% by 1986. Sandia Laboratories has been selected to manage this technology development program, and this paper presents an overview of the program. Program justification which relates well cost to busbar energy cost and to DGE power-on-line goals is presented. Technological deficiencies in current rotary drilling techniques for geothermal wells are discussed. A program for correcting these deficiencies is described.

REVIEW OF THE DRILLING R&D PROGRAM AT SANDIA, SAND78-0704C, H. M. Stoller, Proceedings of Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa, Oklahoma, August 29-31, 1978.

Drilling projects conducted for the Division of Geothermal Energy (DGE) and the Office of Energy Research (OER), both of the Department of Energy (DOE), are described. The DGE Well Technology Program includes drilling, well completion, and high temperature logging instrumentation R&D for geothermal applications. Accomplishments to date include successful laboratory testing of the continuous chain drill and development of temperature, pressure, and flow sondes capable of operation at 275°C. Efforts are also underway to develop high-temperature, high-performance bits, high-temperature drilling fluids, and high-temperature downhole motors. Bearings, seals, and lubricants for use in high-temperature bits and motors are also being developed and tested. Recent results are presented. An OER drilling experiment into a lava lake at Kilauea Iki, Hawaii, is being conducted. Materials and techniques for drilling into an active magma/hydrothermal system are in a preliminary phase of study.

A PROGRAM IN GEOTHERMAL WELL TECHNOLOGY DIRECTED TOWARD ACHIEVING DOE/DGE POWER-ON-LINE GOALS, SAND78-0766, J. Polito and S. G. Varnado, Sandia National Laboratories, September, 1978.

This document presents the material used in an oral presentation to the DOE/Division of Geothermal Energy, which was designed to illustrate the importance of well technology development in reducing geothermal well costs, and to achieve geothermal power-on-line goals. Examination of recent studies of the economics of geothermal energy leads to the conclusion that the overall sensitivity of geothermal power-on-line to well cost is the range of one to two. Current data suggest that a vigorous R&D program in rotary drilling technology can reduce geothermal drilling costs by about 20%, but a reduction of 40-50% is needed to achieve DOE/DGE goals. Research in advanced drilling systems is needed to satisfy this more stringent requirement. This report details some critical technological deficiencies that occur when current rotary drilling techniques are used for geothermal drilling. A broadly based development program directed at correcting these deficiencies is defined.

DRILLING TECHNOLOGY DEVELOPMENT PROGRAM, FISCAL YEARS 1977-1978, SAND78-1226, Charles F. Huff, Sandia National Laboratories, September 1979.

The activities of the Drilling Technology Development Program conducted by Sandia Laboratories for the Division of Fossil Fuel Extraction, Department of Energy (DOE) during FY-77 and FY-78 are described. The three projects actively pursued were High Performance Bit Development -- Polycrystalline Diamond Compact (PDC) Bonding Study; Drilling Instrumentation -- Field Portable High Temperature Pressure Mud Test Equipment; and Environment Resistant Materials -- Coatings on Elastomers and Fatigue Resistance of Steels.

Highlights of FY-77 included successful diffusion bonding of polycrystalline diamond compacts (e.g., Stratapax®) to studs and use of graphite granules as a pressure transfer medium in the diffusion bonding process. The PDC stud assemblies were tested in single point rock cutting experiments that demonstrated the competence of the bond in a fatigue environment. In the instrumentation project, prototype model of a viscometer capable of measuring drilling mud properties at pressures and temperatures up to 20,000 psi (138 MPa) and 500°F (260°C) was completed. The first coatings were deposited on elastomers, showing some enhancement of their service life. Crack growth tests of steels in a sour-gas environment were completed, showing similar fatigue resistance for various techniques of heat treating drill string steels.

During FY-78, commercial sources of metallization for use in the diffusion bonding process were developed. Since the autoclaving is commercially available, the entire process can be accomplished by anyone capable of sealing the container under a high vacuum. The first bit was tested in a laboratory drilling environment. Penetration rates up to 100 fph at 100 rpm were achieved in Carthage Marble, and 72 ft of Sierra White Granite were drilled at rates averaging over 60 fph. The prototype model of the high temperature-pressure viscometer was tested in the laboratory and in the field. Additional coatings were applied to elastomers, and laboratory tests were conducted to determine the effect of the coatings on mechanical properties.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM SEMI-ANNUAL PROGRESS REPORT, OCTOBER 1978-MARCH 1979, SAND79-1499, Samuel G. Varnado, Editor, Sandia National Laboratories, September 1979.

This report describes the progress, status, and results of ongoing research and development within the Geothermal Drilling and Completion Technology Development Program for the period October 1978-March 1979.

THE FEDERAL PROGRAM IN GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT, SAND79-0365A, S. G. Varnado, Sandia National Laboratories, Proceedings of Society of Petroleum Engineers of AIME 54th Annual Technical Conference and Exhibition, September 23-26, 1979, Las Vegas, Nevada.

This paper describes the research and development program being conducted by the U. S. Department of Energy in geothermal drilling and completion technology. Sandia National Laboratories, Albuquerque, New Mexico, manages this program for the Department of Energy. The program currently is funded at a level of approximately five million dollars per year and supports drilling technology development activities at a number of industrial firms throughout the country. This paper presents the scope and goals of the program and describes the on-going R&D programs in high temperature bits, high temperature drilling fluids and high temperature downhole motors.

STATE-OF-THE-ART STUDY OF DRILLING PROBLEMS IN SELECTED SHALES, SAND79-0865C, R. C. Reineke, Sandia National Laboratories, Proceedings of Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology, August 22-24, 1979, Tulsa, Oklahoma.

The Stanley formation of southeastern Oklahoma is believed to contain large quantities of natural gas. Due to the high cost of drilling this formation and due to the low gas production rate from the sands, it is not economical to produce from this formation at the present time. One possible approach to reducing drilling costs is to drill with air and take advantage of the higher penetration rate obtainable. However, this approach tends to create additional problems associated with borehole stability and hole cleaning. This paper summarizes the results of a state-of-the-art study which was directed toward shale drilling problems, air drilling problems, and their reported solutions. Future plans for investigating the effects of various drilling fluids on selected samples of shale are presented.

SANDIA/DOE GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM, SAND79-1398C, J. H. Barnette, Sandia National Laboratories, Transactions of Geothermal Resources Council Annual Meeting, Vol. 3, September 1979, p. 31, Reno, Nevada.

The high cost of drilling and completing geothermal wells is an impediment to the development of geothermal energy resources. Technological deficiencies in rotary drilling techniques are evidenced when drilling geothermal wells. The Division of Geothermal Energy (DGE) of the U. S. Department of Energy (DOE) has initiated a program aimed at developing new drilling and completion techniques for geothermal wells. The goals of this program are to reduce well costs 25% by 1982 and 50% by 1986.

Sandia Laboratories has managed this technology development program since October, 1977, and this paper presents an overview of the program. A statement of program goals and structure is given. The content of the FY-79 program is presented and recent results of R&D projects are given. Plans for development of an advanced drilling and completion system are discussed.

GEOTHERMAL DRILLING RESEARCH IN THE UNITED STATES, SAND79-1756C, S. G. Varnado, A. B. Maish, Sandia National Laboratories, Proceedings of Geotechnical and Environment Aspects of Geopressure Energy, Engineering Foundation Conference, January 13-18, 1980, Sea Island, Georgia.

This paper describes the research and development program being conducted by the U. S. Department of Energy in geothermal drilling and completion technology. Sandia National Laboratories manages this program for the Division of Geothermal Energy of the U. S. Department of Energy. This paper presents the scope and goals of the program and describes the programs in high temperature bits, drilling fluids, and downhole motors.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM SEMI-ANNUAL PROGRESS REPORT, APRIL-SEPTEMBER 1979, SAND79-2397, Samuel G. Varnado, Editor, Sandia National Laboratories.

This report describes the progress, status, and results of ongoing research and development within the Geothermal Drilling and Completion Technology Development Program for the period April-September 1979.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT, OCTOBER-DECEMBER 1979, SAND79-2398, Samuel G. Varnado, Editor, Sandia National Laboratories.

This report describes the progress, status, and results of ongoing research and development within the Geothermal Drilling and Completion Technology Development Program for the period October-December 1979.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT, JANUARY-MARCH 1980, SAND80-0703, Samuel G. Varnado, Editor, Sandia National Laboratories.

This report describes the progress, status, and results of ongoing research and development within the Geothermal Drilling and Completion Technology Development Program for the period January-March, 1980.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT, APRIL-JUNE 1980, SAND80-1234, Samuel G. Varnado, Editor, Sandia National Laboratories.

This report describes the progress, status, and results of ongoing research and development within the Geothermal Drilling and Completion Technology Development Program for the period April-June, 1980.

CONTINENTAL DRILLING IN THERMAL REGIMES: DRILLING IN-SITU DIAGNOSTICS AND SAMPLING, SAND80-2164, R. K. Traeger, S. G. Varnado, A. F. Veneruso, Sandia National Laboratories, Proceedings of Fall Meeting, American Geophysical Union, San Francisco, California, December 8-12, 1980.

The current status of drilling technology, in-situ diagnostics and formation/fluid sampling is reviewed in context to the Continental Scientific Drilling Program. A hypothetical, 7 km deep scientific drill hope is used to identify required technological developments, potential research problems imposed by drilling or field hardware and major cost factors.

Gas wells to 9 km in depth with maximum temperatures of 200-225°C have been drilled at costs of $5-40 million. Conventional logging instruments have been used to 150°C with dewared instrumentation used to 220°C. New commercial technology will be available for logging to temperatures of 225°C and advanced instrumentation studies are expected to provide downhole capabilities to 300°C. Coring and in-situ fluid sampling has been limited to low temperatures and pressures of 0.5 to 1.5 kbar.

Technology developments are needed in drilling, instrumentation and sampling for temperatures exceeding 300-350°C. Since developments will be site specific (temperature, pressure, geology, environment), location of the proposed hole and extensive geological, geophysical and geochemical studies are needed to focus hardware development.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM ANNUAL PROGRESS REPORT, OCTOBER 1979-SEPTEMBER 1980, SAND80-2179, Samuel G. Varnado, Editor.

This report describes the progress, status, and results of ongoing Research and Development within the Geothermal Drilling and Completion Technology Development Program for the period October 1979-September 1980.

II. LOGGING INSTRUMENTATION

Introduction

The Geothermal Logging Instrument Development Program's goal is to develop high temperature electronic components and downhole instrumentation that are required to log geothermal wellbores in order to evaluate the production potential of geothermal resources. Sandia National Laboratories conducts this program for the Department of Energy, Division of Geothermal Energy. Both generic electronic components and specific production logging tools have been developed. The generic components include: resistors, capacitors, semiconductors, and hybrid microelectronic circuitry. Sensors and transducers have been developed which provide measurements of temperature, pressure, flow velocity, and acoustic waves. The prototype logging tools include: temperature, pressure, flow, caliper, and fracture mapping using the acoustic borehole televiewer.

A. Logging Tools

HIGH TEMPERATURE INSTRUMENTATION, A. F. Veneruso, Sandia National Laboratories, SAND77-1895J, Proceedings of Invitational Well-Testing Symposium, Berkeley, California, October 19, 1977.

Methods for obtaining geothermal borehole measurements and making appropriate interpretations are limited at present by technical deficiencies in that logging tools developed for the oil and gas industry rarely encounter temperatures above 150°C. Also, most of the available logging tools, cables, and seals are rated to only 180°C, whereas in geothermal wells temperatures frequently range up to 350°C. The Geothermal Logging Development Program being conducted by Sandia Laboratories for DOE's Division of Geothermal Energy is reviewed. This program is an industry-based effort to develop and apply the high temperature instrumentation which is needed by the wireline logging industry to serve a rapidly expanding geothermal market. In order to satisfy critical existing needs, the near-term goal is to develop instrumentation for use at or above 275°C in pressures up to 48.3 MPa (7,000 psi) by the end of FY-80. The long-term goal is for operation up to 350°C and 138 MPa (20,000 psi) by the end of FY-82. To meet these goals, existing hardware will be upgraded and new components will be developed and evaluated in critically needed prototype tools such as the temperature, flow rate, and high resolution downhole pressure sondes.

SOLID STATE 275°C GEOTHERMAL TEMPERATURE TOOL, SAND78-1037, K. R. White, Sandia National Laboratories.

Development of geothermal energy sources requires accurate and interpretable data describing the temperature and other characteristics of the fluid column in a geothermal borehole. Temperatures in these fluids are known to approach 275°C in many geothermal boreholes. This report discusses the advantages and disadvantages of two types of previously available instruments for measuring the borehole temperature profile: analog temperature tools which are primarily a sensor connected to a long logging cable where the sensor's output is an analog of the temperature in the borehole, and digital temperature tools which consist of a sensor and an analog-to-digital converter connected to the logging cable.

DEVELOPMENT OF A HIGH RESOLUTION DOWNHOLE PRESSURE INSTRUMENT FOR HIGH TEMPERATURE APPLICATIONS, SAND78-1550, E. P. EerNisse, T. D. McConnell, A. F. Veneruso, Proceedings of Lawrence Berkeley Laboratory International Well Testing Symposium, Berkeley, California, October 25, 1978.

As part of the Geothermal Logging Instrumentation Development Program being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy, high resolution, quartz crystal based, downhole pressure instruments are being developed. Under a joint no-cost contract, Sandia and Paroscientific, Inc., of Redmond, Washington, are working to upgrade a Paroscientific transducer for operation at 275°C. In addition, Sandia Laboratories has been investigating various design configurations and fabrication techniques for high temperature quartz resonators and their associated electronic circuits. The goal of these efforts is to achieve a resolution of 0.01 psi in an 0-7000 psi range and in temperatures up to 275°C. The progress and plans for this project will be reviewed and hardware samples will be displayed.

HIGH TEMPERATURE INSTRUMENTATION FOR GEOTHERMAL APPLICATIONS, SAND78-0668C, A. F. Veneruso, H. M. Stoller, Sandia National Laboratories, Geothermal Resources Council, Transactions, Vol. 2, July 1978, p. 679.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities (∿ 180°C) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging Instrumentation Development Program being conducted by Sandia Laboratories for the Department of Energy (DOE), Division of Geothermal Energy is an industry based effort to develop and apply the high temperature instrumentation needed to make geothermal borehole measurements. The near-term goal is to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7,000 psi); subsequent goals are to extend the capabilities to 350°C and 138 MPa (20,000 psi). Working closely with geothermal producers, logging service companies are conducting R&D to correct technical deficiencies so they may adequately serve the growing geothermal market. The basic impediments they face involve special technologies which are not normally required in their trade and for which there are insufficient incentives for them to develop. These technologies are precisely those which are being developed by this program; components development activities are directed toward stimulating industries' own inventions and field applications of geothermal logging instruments having improved reliability, appropriate size, reasonable cost and performance versatility which encompasses not only geothermal but conventional petroleum and hot, deep natural gas logging as well. Tools to be upgraded and/or developed include temperature, flow rate, high resolution downhole pressure, caliper and fracture mapping sondes.

MONOCONDUCTOR CABLES AND CABLEHEAD, Joe A. Coquat, Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, Houston, Texas, December, 1979, SAND80-0834.

A significant problem in the overall task of high temperature instrumentation for geothermal logging is a reliable, low noise interconnect system between the up-hole (cool) electronics and the downhole (hot) electronics. A project to develop such a single conductor based interconnect system is discussed including successes to date, on-going work, and plans for the near future. The project is logically divided into two major areas: the cablehead and the cable itself. A high temperature (275°C) corrosion resistant head developed with Gearhart Owen Industries Inc. (GOI) has demonstrated the ability to solve electrical communications problems (leakage resistance) generally associated with the cable-to-sonde interface while logging hostile environment geothermal wells. A commercial TFE teflon® insulated cable has been purchased from the Vector Cable Company and has been successfully used to 300°C in a geothermal field test and laboratory tested to its rated specification of 315°C for 9 hours.

A two-year program to develop and test a long-term, high temperature, and high reliability cable based on non-conventional logging cable technologies has begun. A two-fold goal has been determined: 1) fabricate a production logging cable for continuous application for at least one year, and 2) produce a highly reliable logging cable capable of extended repeated use.

UPGRADING MECHANICAL TOOLS SURVEY CLOCKS, B. H. Major, Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, Houston, Texas, December 1979, SAND80-0834, p. 231.

Development of the earth's high temperature geo-energy resources is dependent on sufficient well logging to obtain essential physical and chemical properties of the well. Methods for obtaining this information are limited at present by technical deficiencies in that the logging tools in current use were developed for the oil and gas industry. Such instruments rarely encounter temperatures above 150°C; whereas gas wells frequently go to 180°C and some geothermal wells up to 350°C.

The "Amerada" type subsurface recording gauges have been the staple instruments of the oil and gas industry for several years. The same instruments are currently in use by the growing geothermal industry. However, at elevated temperatures, significant reductions in reliability and tool life have been reported.

A primary concern of the "Amerada" type instruments is its survey clock, which often fails in well logging at high temperature. Much test time and labor is lost as a result of a single failure of the clock mechanism. Currently, increased reliability is sought by either restricting the log to three hours, or by utilizing two gauges connected in tandem to ensure at least one successful log. However, because of the large number of "Amerada" type instruments currently in use by industry, it would be best to upgrade them for high temperature reliability. This should be accomplished with a minimum of redesign and rework.

HOSTILE ENVIRONMENT TEST SYSTEM FOR LOGGING CABLES, Leslie C. Rose, Aerospace Research Corporation, Roanoke, Virginia, under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, Houston, Texas, December 1979, SAND80-0834, p. 101.

A hostile environment test system for well logging cables has been developed by Aerospace Research Corporation. The system is capable of subjecting a short section (approximately 3 ft) of either multi or single conductor cable to various combinations of pressure, temperature and tension while submerged in various fluids such as water, sodium chloride solution or the liquid portion of drilling mud. A system for using a hydrogen sulfide solution has been installed and tested at ambient temperature and pressure.

UPGRADING AMERADA-TYPE SURVEY CLOCKS FOR HIGH-TEMPERATURE GEOTHERMAL SERVICE, Bruce H. Major and Clifford L. Witten, Sandia National Laboratories, Geothermal Resources Council Transactions, Vol. 4, September 1980, p. 361.

The "Amerada" type subsurface recording gauges have been used by the oil and gas industry for many years. These mechanical logging instruments are currently used by the growing geothermal industry. As the gauges were designed for service in low-temperature oil and gas wells, a significant number of failures are occurring at elevated geothermal temperatures. The spring driven mechanical survey clocks appear to be the primary cause of the failures. The clock mechanisms tend to stop or lock up when exposed to temperatures as high as 300°C. This paper summarizes a project that was undertaken to upgrade the survey clocks

to 300°C capability. The major problems causing clock failure were identified and corrected by straightforward design and modifications together with special lubrication of the moving parts. Several clocks so modified performed reliably, both during laboratory oven tests and during field tests that were performed in actual geothermal wells at temperatures up to 330°C.

GEOTHERMAL PRODUCTION LOGGING TOOLS -- COMPONENTS, PROTOTYPE FIELD TESTING AND COMMERCIALIZATION, A. F. Veneruso, Sandia National Laboratories, Society of Petroleum Engineers Paper, 55th Annual Technical Conference and Exhibition, September 21-24, 1980, Dallas, Texas.

This paper demonstrates that commercial components and prototype designs are now available to build geothermal production logging tools for operation to 275°C. Prototype temperature, pressure, and flow tools have been built and successfully field tested to 275°C. The design, fabrication, and field operation of these instruments are presented along with a list of commercial sources for the components and circuits employed.

PRESSURE MEASUREMENTS IN LOW PERMEABILITY FORMATIONS, A. F. Veneruso and T. D. McConnell, Sandia National Laboratories, Proceedings for the Third Invitational Well Testing Symposium, Lawrence Berkeley Laboratory, March 26-28, 1980, Berkeley, California.

This paper examines the performance requirements and identifies candidate hardware implementations for pressure instrumentation that is needed to provide well test data in low permeability formations. Low permeability values are typically defined to be less than 1 microdarcy and are usually encountered in hard rock formations, such as granite, that are of interest in hot dry rock geothermal, deep exploration drilling, and fluid waste disposal. Groundwater flow in these "tight" formations has been shown to be dominated by flow-through fractures rather than through the formation's intrinsic permeability. In these cases, we cannot use Darcy's law or the usual dimensionless coefficients to estimate the expected scale factors and dynamic responses necessary to properly select and set up the wellbore pressure instrument. This paper shows that the expected instrument responses can be estimated using some recent work by Wang, Narashimhan, and Witherspoon. This paper further describes the minimum electronic capability that the downhole pressure instrument must have in order to provide the required measurement resolution, dynamic range, and transient response. Three specific hardware implementations are presented based on the following transducers: a quartz resonator, a capacitance gauge, and a resistance strain gauge.

UPGRADING THE ACOUSTIC BOREHOLE TELEVIEWER FOR GEOTHERMAL FRACTURE MAPPING, Fred E. Heard, Sandia National Laboratories, Geothermal Resources Council, Transactions Vol. 4, September 1980, p. 341.

The importance of fracture characterization in geothermal logging has long been recognized. The acoustic borehole televiewer is probably the single most useful tool for determining location, orientation, and characterization of fractures. However, since the televiewer was

developed for low temperature oil and gas exploration, it has not been capable of reliable operation at geothermal temperatures. This paper reviews the theory of operation of the acoustic televiewer, identifies the problems associated with its operation at both high and low temperatures, and reviews a program to upgrade the tool. Major results of the program have been: 1) a high temperature acoustic transducer, 2) an improved acoustic window, 3) more reliable electronics, and 4) the elimination of troublesome slip rings.

PRESSURE INSTRUMENTATION FOR GEOTHERMAL BOREHOLE MEASUREMENTS, T. D. McConnell, Sandia National Laboratories, Geothermal Resources Council, Transactions Vol. 4, September 1980, p. 365.

Accurate geothermal logging requires pressure measurements and resolutions down to 0.01 psi in environments of up to 275°C and 15,000 psi. This paper examines the characteristics of several basic types of pressure transducers and compares them to these requirements. Specific deficiencies are identified such as thermal stability and resolution limitations; R&D activities and results correcting these deficiencies are discussed.

B. High Temperature Devices

SEMICONDUCTORS AND 300°C HYBRID MICROCIRCUITS, SAND77-0392, J. D. McBrayer, D. W. Palmer, and C. R. Hickam, Sandia National Laboratories, Proceedings of ISHM77 International Society of Hybrid Microcircuits Meeting, October 24-26, 1977, Baltimore, Maryland.

As part of a program to develop hybrid microcircuits capable of operation from +25-300°C in a geothermal well, it was necessary to investigate semiconductor devices. Three studies are described which allowed routine use of devices at high temperatures: 1) Si and GaAs devices were characterized from +25-300°C and for 1000 hours at 300°C, 2) the degradation rates of Al wire bonds to thick films and to special buffer pads were measured, and 3) methods of prescreening active devices at high temperatures before committing them to a hybrid were developed. These studies revealed that among commercial devices tested only discrete Si JFETs and MOSFETs were acceptable for high temperature circuits. In contrast, Si bipolar, Si integrated circuits, and GaAs FETs were not suitable. Hybrids functioning at 300°C for 500 hours were fabricated as a result of this work.

ACTIVE DEVICES FOR HIGH TEMPERATURE MICROCIRCUITRY, SAND77-1145, D. W. Palmer, B. L. Draper, J. D. McBrayer, and K. R. White, Sandia National Laboratories, February 1978.

As part of a program to develop high temperature electronics for geothermal well instrumentation, a number of solid state diode and transistor types have been characterized from room temperature to 300°C. The temperature dependence and aging stability of transport and leakage properties were measured. Included in the study were silicon diodes, bipolar transistors, JFETs, MOSFETs, and GaAs MESFETs and JFETs. In summary, the results are: diodes and bipolar transistors became extremely leaky at high temperature and are therefore of limited use; silicon MOSFETs and GaAs devices showed unacceptable aging instabilities at high temperatures; silicon JFETs from certain manufacturers were sufficiently stable and had suitable temperature dependent characteristics so that operational circuits could be made.

Comparisons were made of experimental device characteristics and those predicted by theory. The theoretical calculations were done using standard equations revised to include appropriate temperature dependent parameters. Close agreement between theory and experiment was found, indicating that unexpected high temperature effects were insignificant. In order to facilitate the use of devices in high temperature hybrids, it was necessary to develop bonding and prescreening techniques. A large variance of JFET 300°C operating parameters was found even within a single production lot. Consequently, high temperature prescreening allowed each circuit to be specifically "pretuned." Standard solder, epoxy, and chip and wire attachment technologies were not functional at 300°C. Gold-germanium solder, aluminum wire to Dupont 9910 gold film, and diffusion barrier pads were developed to allow high temperature attachment.

CMOS TEST CHIP, SAND78-1390, J. D. McBrayer, Sandia National Laboratories, August 1978.

To support an effort to develop high temperature electronics for geothermal well instrumentation, and to develop a complete understanding of radiation effects on CMOS circuits, a CMOS test chip has been designed. This chip will be the test bed for determining the feasibility of CMOS circuitry sustaining 1000 hours at 300°C. Furthermore, this same chip will be used to understand latch-up phenomenon, and other effects of CMOS circuits under radiation environments. This test chip will be manufactured at Sandia Semiconductor Development Laboratory.

HIGH-TEMPERATURE COMPLEMENTARY METAL OXIDE SEMICONDUCTORS (CMOS), SAND79-1487, J. D. McBrayer, Sandia National Laboratories.

Silicon CMOS devices were studied, tested, and evaluated at high temperatures to determine processing, geometric, operating characteristics, and stability parameters. After more than 1000 hours at 300°C, most devices showed good stability, reliability, and operating characteristics. Processing and geometric parameters were evaluated and optimization steps discussed.

BEHAVIOR OF SILICON DEVICES AT HIGH TEMPERATURES, Bruce L. Draper, Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 111, SAND80-0834.

In the early stages of the high temperature electronics program at Sandia Laboratories, the selection of active devices received much attention. The use of bipolar transistors was largely avoided because it was felt that the collector-base leakage currents were excessive. MOS devices were shunned because of large drain-substrate leakage currents and large, uncontrolled flat-band voltage shifts created by mobile charge in the gate oxide. In fact, JFETs seemed to be the only acceptable active devices for long term (> 1000 hours) high temperature use. In general, they displayed a well defined zero-temperature-coefficient (ZTC) region and suffered from no inherent instability mechanisms. For these reasons, downhole instrumentation designed at Sandia uses discrete JFETs exclusively. However, computer modeling, device redesign, and better fabrication techniques have now shown that silicon MOSFETs may be used at temperatures well in excess of 300°C. Likewise, Harris Semiconductor is also now developing a 300°C op-amp using a dielectrically isolated bipolar technology. Hence, it is becoming apparent that almost any silicon device type, if properly designed, can be used at temperatures near 300°C.

QUARTZ RESONATOR PRESSURE TRANSDUCER FOR GEOTHERMAL WELL LOGGING, Errol P. EerNisse, Quartez, Inc., and T. D. McConnell, Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 209, SAND80-0834.

Sandia Laboratories is developing a quartz resonator pressure transducer for geothermal well logging applications. The resulting pressure tool will be designed for use in wells at up to 275°C (527°F) and pressure up to 52 MPa (7500 psi).

COMPATIBLE THIN-FILM COMPONENTS FOR HIGH-TEMPERATURE ELECTRONICS, L. S. Raymond, L. N. Nelson, D. J. Hamilton and W. J. Kerwin, University of Arizona, under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 125.

This paper describes the fabrication of thin-film resistors which can operate at 500°C and capacitors which can operate at 350°C. These components are deposited by Low Pressure Chemical Vapor Deposition (LPCVD) and are compatible with each other as well as with MOS devices. Fabrication and modeling of metal-gate NMOS devices which operate at 300°C is also discussed.

COMPOUND SEMICONDUCTOR FOR HIGH TEMPERATURE ACTIVE DEVICES, O. Eknoyan, Texas A&M University under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 129.

High-temperature semiconductor devices are desirable in a number of specialized systems. Among these are instrumentation packages used in deep well logging, aircraft engine-control, and nuclear reactor power generators. The range of application clearly depend on the availability, reliability, and cost of these devices. To date, no commercial active devices have been found useful for operation above 300°C where the need in geothermal logging lies. This limitation arises from the chosen semiconductor material and/or processing techniques utilized in the realization of final devices. The criteria for choosing an appropriate starting semiconductor material for high temperature operation is the use of a wide energy bandgap semiconductor materials. On the other hand, the design of such devices requires a special attention in processing techniques which are not normally considered. This is especially true with respect to dopant species (for junction formation), contact metallization and passivation (for surface protection).

NEW ACOUSTIC SENSOR MATERIALS FOR A GEOTHERMAL BOREHOLE TELEVIEWER, James W. Wonn, Westinghouse R&D Center, Pittsburgh, Pennsylvania, under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 219.

The borehole televiewer (BHTV) is a well logging tool originally developed and used for fracture mapping and characterization in petroleum wells. A geothermal workshop report issued in 1975 identified the need for upgrading the environmental tolerance of the BHTV to permit logging under near-term DOE goal conditions of 275°C (527°F), 7000 psi, and in the corrosive geothermal fluid. Presently, commercial versions of the BHTV have a maximum advertised temperature rating of 150°C (302°F) and are not designed for exposure to highly corrosive fluids.

EXTENSION OF HIGH-TEMPERATURE ELECTRONICS, B. L. Draper and D. W. Palmer, Sandia National Laboratories, IEEE Trans. on Components, Hybrids, and Mfg. Technology, Vol. CHMT-2, No. 4, December 1979.

Commercial and Sandia fabricated silicon MOSFETs, thick-film resistors and capacitors, and magnetic components were investigated in an effort

to increase the versatility of micro-electronics used at 300°C and to form a foundation for a higher temperature technology. Commercial MOSFETs were found susceptible to parameter drifts and have unacceptable electrical characteristics when tested at 300°C, whereas redesigned low alkali impurity devices were able to maintain stable operation at 300°C for 1000 hours with improved characteristics. Thus, although MOSFETs are prone to aging, it is possible to use fabrication procedures which allow MOSFET use at high temperature. A specially developed ceramic filled, high silica frit dielectric thick-film material exhibited a sufficiently high resistivity to permit development of 300°C, 1.0 micro F capacitors. Procedures were developed to make this material compatible with the multilayer brick capacitor format which is necessary for miniaturization. Both this dielectric and a ruthenium-based resistor material were shown useful to 500°C. In addition, a spectrum of magnetic components was qualified for use at 500°C.

GaAs OHMIC CONTACTS FOR HIGH TEMPERATURE DEVICES, J. A. Coquat and D. W. Palmer, Sandia National Laboratories, O. Eknoyan and W. B. Van der Hoeven, Texas A&M College, Proceedings of IEEE Electronics Components Conference, April 28, 1980, San Francisco, California.

Instrumentation requirements for geothermal wells, jet engines, and nuclear reactors have exceeded the high temperature capability of silicon devices. As one part of a program to develop high temperature compound semiconductor devices, four basic ohmic contact systems for n-type GaAs have been evaluated for contact resistance as a function of temperature (24-350°C) and time (at 300°C): Ni/AuGe; Ag/Si and Ag/Ni/Si; Al/Ge and Al/AlGe; and Au/Nb/Si and Pt/Nb/Si. Optimization of processing parameters produced viable high temperature contacts with all but the Al/Ge systems. Aging at 300°C changed the contact resistivity in only the Ag/Ni/Si contacts. Film adhesion was excellent for the Al/Ge, Ni/AuGe, and Ag/Si systems as measured with ultrasonic Al wire bond pull strengths. Lower adhesion was noticed with Nb/Si systems measured with gold wire bond pull strengths.

SEMICONDUCTORS FOR HIGH TEMPERATURE ACTIVE DEVICES -- SILICON, GaAs, and GaP, SAND80-0379, Proceedings of Electro/80 Professional Program, May 13-15, 1980, Boston, Massachusetts.

This paper reviews developments during the past three years in the area of high-temperature active semiconductor devices for use at 275°C in instrumentation needed to characterize geothermal resources. Surveys of silicon bipolar, MOS, and JFET devices operated at high temperature and developmental work on high temperature silicon CMOS logic and DI analog circuits are reviewed. The initial results of developmental work on GaAs and GaP diodes are discussed. These efforts have identified several promising devices for high temperature applications; however, further development is required to resolve such problems as excessive leakage currents, metallization degradation, device stability, and long-term aging.

HIGH TEMPERATURE ELECTRONICS AND INSTRUMENTATION SEMINAR PROCEEDINGS, Anthony F. Veneruso and Charles Arnold, Sandia National Laboratories, Richard S. Simpson, University of Houston, Editors, December 1979, Houston, Texas, SAND80-0834.

This report presents the results of a two-day seminar that reviewed the state-of-the-art and the recent substantial progress in High Temperature Electronics and Instrumentation. Over 350 people participated in this meeting which was held in Houston, Texas, December 3-4. This seminar was tailored to address the needs of the borehole logging industry and to stimulate the development and application of this technology, for logging geothermal, hot oil and gas, and steam injection wells. The technical sessions covered the following topics: hybrid circuits, electronic devices, transducers, cables and connectors, materials, mechanical tools and thermal protection. The frontiers of this technology were shown to be rapidly moving beyond the 125°C Mil-Spec boundary. Special "hostile environment" instruments routinely operate up to 180°C, a few prototype systems have been field tested to 275°C, and new development is underway for 300°C hybrid and integrated circuits. Sandia National Laboratories organized and conducted this seminar with funding provided by the U. S. Department of Energy's Division of Geothermal Energy and Division of Fossil Fuel Extraction.

PROGRESS REPORT ON GaP, GROWN JUNCTION, HIGH TEMPERATURE DIODES, R. J. Chaffin, Sandia National Laboratories, SAND80-1763, August 1980.

This report discusses current results of an effort to develop GaP (Gallium Phosphide) diodes for high temperature, > 275°C, applications. It discusses the theory, fabrication and testing of devices made at Sandia National Laboratories.

LASER-ANNEALED GaP OHMIC CONTACTS FOR HIGH-TEMPERATURE DEVICES, SAND80-2679, O. Eknoyan, W. Van der Hoeven, T. Richardson, and W. A. Porter, Texas A&M University and J. A. Coquat, Sandia National Laboratories.

The results of successful Nd:YAG laser annealed ohmic contacts on n-type GaP are reported. Comparisons on identical laser and thermal annealed contacts on the same substrates are performed. In addition aging investigations are also studied. The results indicate that laser annealed contacts have far superior electrical characteristics, much better surface morphology and are substantially more stable with aging than the same but thermally alloyed ones.

PERFORMANCE OF DIGITAL INTEGRATED CIRCUIT TECHNOLOGIES AT VERY HIGH TEMPERATURES, J. L. Prince, E. A. Rapp, J. N. Kronberg, and L. T. Fitch, Clemson University and B. L. Draper, Sandia National Laboratories, IEEE Trans. on Components, Hybrids, and Mfg. Technology, Vol. CHMT-3, No. 4, December 1980.

Results of detailed investigations of the performance and reliability of digital bipolar and CMOS integrated circuits over the 25-340°C range are reported. Included in these results are both parametric

variation information and analysis of the functional failure mechanisms. Although most of the work was done using commercially available circuits (TTL and CMOS) and test chips from commercially compatible processes, some results of experimental simulations of dielectrically isolated CMOS are also discussed. In general, it was found that commercial Schottky clamped TTL, and dielectrically isolated, low power Schottky-clamped, functioned to junction temperatures in excess of 325°C. Standard gold doped TTL functioned only to 250°C, while commercial, isolated I^2L functioned to the range of 250-275°C. Commercial junction isolated CMOS, buffered and unbuffered, functioned to the range of 280-310°C+, depending on the manufacturer. Experimental simulations of simple dielectrically isolated CMOS integrated circuits, fabricated with heavier doping levels than normal, functioned to temperatures in excess of 340°C. High temperature life testing of experimental, silicone-encapsulated simple TTL and CMOS integrated circuits have shown no obvious life limiting problems to date. No barrier to reliable functionality of TTL bipolar or CMOS integrated circuits at temperatures in excess of 300°C has been found.

C. High Temperature Circuits

HYBRID MICROCIRCUITRY FOR 300°C OPERATION, D. W. Palmer, Sandia National Laboratories, IEEE Trans. on Parts, Hybrids, and Pkg., Vol. THP-13, No. 3, September 1977.

Microelectronic instrumentation for geothermal well logging must operate in ambient temperatures up to 300°C for several hundred hours. This study involved an extensive survey of 25-300°C operation of resistors, capacitors, conductors, interconnections, and active devices. Three major selection criteria were: 1) part lifetime of at least 1000 hours at 300°C; 2) minimum change in electrical parameters from 25-300°C; 3) availability to the common circuit builder (no one of a kind). Certain thick film resistors, capacitors, and conductors were found compatible with such high-temperature operation. In addition, reconstituted mica and aluminum solid electrolytic capacitors were found useful up to 300°C. Simple circuits for geothermal temperature logging tool have been fabricated using these hybrid materials, components, and Si MOS and JFET devices. Oven tests show satisfactory stability from 25-300°C and at least 100-h circuit operation at 300°C.

EXTREME TEMPERATURE RANGE MICROELECTRONICS, D. W. Palmer, R. C. Heckman, Sandia National Laboratories, IEEE Trans. on Components, Hybrids, and Mfg. Technology, Vol. CHMT-1, No. 4, December 1978.

Downhole geothermal instrumentation must operate over a large temperature range. The technology and capabilities of room temperature to 300°C hybrid and printed-circuit (PC) board electronics that were develped during the last two years to meet that need are summarized. To ensure rapid widespread commercialization, this technology was developed, insofar as possible, using commercially available components, devices, and materials. Initial extensive high-temperature characterization revealed that selected thick-film passive components and silicon junction-field-effect transistors had electrical parameters sufficiently insensitive to temperature change and sufficiently constant in time at high temperatures to form the backbone of this circuitry. Attachment techniques needed to be developed, since standard methods failed at high temperatures. Similarly, circuit design innovations were needed because of the restricted list of parts. Voltage regulators, line drivers, voltage comparators, special purpose amplifiers and multiplexers were constructed and operated over the 25-300°C temperature range. Temperature and pressure monitoring instruments using these circuits have been used for downhole measurements in geothermal wells. Methods of fabrication, circuit performance, and the scope of future work are discussed.

DESIGN AND PERFORMANCE OF GEOTHERMAL HYBRID MICROCIRCUITS, D. W. Palmer, Sandia National Laboratories, 1978 MID-CON Program, Booklet 21, December 12, 1978.

Geothermal well logging electronic instrumentation requires carefully chosen materials and layout procedures to ensure hybrid operation from 25-300°C for at least 100 hours. Material selection involved thick film inks, transistor chips, and packaging compounds. Commercial thick film materials were found which tolerate extreme temperature operation: "plague-free" fritless golds, resistor compositions with temperature coefficients of resistance optimized at 150°C, and high

melting temperature-low ion mobility dielectric inks. Exhaustive semiconductor device surveys indicate the silicon junction field effect devices exhibit a zero temperature coefficient operational bias region from 25-300°C and acceptable drift during 1000 hours at 300°C. Attachment of substrates into hermetic packages is achieved with gold-germanium preforms or low melting temperature glaze, and package lids are preform-soldered or welded on in an inert atmosphere.

Several layout techniques are used which facilitate assembly and enhance reliability: 1) large rectangular resistor areas enhance stability and extend trimming range, 2) potential resistor bypasses extend the range of trimming, 3) large die pads allow chip replacement, 4) large wire bonding pads permit diffusion barrier attachment, and 5) isolated transistor patterns allow temperature characterization before commitment to the circuit. Using these materials and layout techniques, instruments to measure downhole temperature, pressure, and flow have been developed and tested. Field performance and future directions will also be discussed.

HIGH TEMPERATURE CHARACTERISTICS OF COMMERCIAL INTEGRATED CIRCUITS, J. L. Prince, E. A. Rapp, J. W. Kronberg, and L. T. Fitch, Clemson University under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 115, SAND80-0834.

Requirements on active electronic components for the hostile downhole environment of geothermal wells are extreme. One requirement is the ability to function reliably at very high ambient temperatures (up to 325°C) for many tens of hours. The high temperature functional capability of various discrete silicon components has been established by earlier work and some information is available on the high temperature performance of integrated circuits (ICs). System requirements dictate eventual use of IC components. The work described here is directed toward establishing the high temperature performance and reliability capabilities of diverse IC technologies, particularly those suitable for digital IC fabrication, and determining the limiting mechanisms and characteristics of the technologies for high temperature application. Further work will lead to the generation of design rules, or at least principles, for high temperature IC design and fabrication.

HIGH TEMPERATURE ANALOG INTEGRATED CIRCUITS, J. D. Beasom, Harris Semiconductor, Melbourne, Florida, under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 123, SAND80-0834.

Commercial integrated circuits have been designed, manufactured and specified to operate only over the temprature range -55°C to 125°C. This range has been satisfactory for the vast majority of military and commercial applications; however, there are some applications such as well logging, engine instrumentation and industrial controls where higher temperatures are encountered. Users in these areas have been forced to characterize various available parts in search for those which may function adequately at the temperature of their application and then test out suitable parts from the manufacturers production. They have had no assurance that the circuits would be reliable at high temperature, nor any that they would continue to find functional parts in future purchases.

COMMERCIAL FABRICATION OF 275°C HYBRID MICROCIRCUITS, Michael G. Reagan, Teledyne Philbrick, Dedham, Massachusetts, under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 65, SAND80-0834.

Teledyne Philbrick was contracted by Sandia Laboratories in the fourth quarter of 1978. The objective of this contract was to demonstrate the ability to commercially fabricate high temperature hybrid microcircuits. The contract called for the production of a +15V regulator capable of operation to 300°C for a minimum of 100 hours. At that time, Sandia had completed the major portion of the electrical design and had resolved numerous mechanical problems. The challenge that awaited Teledyne Philbrick was the investigation and resolution of the remaining mechanical and electrical problems, and to identify techniques that would yield the efficient and reliable fabrication of 300°C hybrid microcircuits.

HIGH TEMPERATURE THICK FILM RESEARCH, R. W. Vest, Purdue University under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 57, SAND80-0834.

Hybrid microelectronics appears to be the most promising approach for the downhole electronics required for geothermal well logging, and thick film is the logical technology for the passive components of the hybrids. Since thick film circuits are typically processed at temperatures of 800°C and above, it might be expected that they would perform satisfactorily and remain stable at temperatures well above 300°C. However, this is not the case because thick film resistors and capacitors are non-equilibrium systems which are optimized for use in a lower temperature range, typically -55°-125°C. Commercially available materials have much larger temperature coefficients at higher temperatures than in their optimum range, and exhibit an irreversible drift of their properties at temperatures much above 300°C. The research at Purdue was undertaken to better understand the phenomena which occur in thick film resistors and capacitors in the temperature range 350-500°C, and to apply the knowledge gained to the development of resistors and capacitors which have acceptable temperature coefficients and which exhibit minimal drift after extended periods at high temperatures. The basic approach has been to select systems which perform well at normal use temperatures, and to make small changes in the materials which our models predict are limiting the performance at elevated temperatures.

HIGH-TEMPERATURE ELECTRONICS -- AN OVERVIEW, Richard C. Heckman, Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 39, SAND80-0834.

The purpose of this paper is to provide an overview of contemporary high-temperature electronics. To that end, it contains brief remarks on its history, an enumeration of the groups or individuals known to us who are now active in the field with their interests and objectives, a discussion of the current state of the art, and an attempt to identify the major areas where new developments are needed for the future.

HARDENING MICROCIRCUITS AGAINST 300°C, YESTERDAY AND TOMORROW, D. W. Palmer, Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 53, SAND80-0834.

Although high temperature electronics had sporatic popularity during the 50's and 60's, a sustained effort on high temperature microelectronics was not initiated until May 1976, when the effort at Sandia Laboratories began. With each subsequent advance in high temperature technology, more notice and participation were generated, until today's effort which involves many industrial and government engineers from researchers to manufacturers. To help coordinate this broad development it becomes important to document both the history and future direction of Sandia's effort. To that end this paper will describe the technological approaches that have been taken at Sandia, what the present capabilities are in the lab and field, and where development is leading.

275°C THICK-FILM HYBRID MICROCIRCUITRY FABRICATION TECHNOLOGY, SAND80-0078, P. A. Bonn, D. W. Palmer, Sandia National Laboratories, March 1980.

High temperature electronics is needed for geothermal well logging tools, jet engine monitors, nuclear reactor instruments, and fossil fuel exploration and production systems. This report describes the step-by-step fabrication technology of thick-film hybrids useful for at least 1000 hours at 275°C. Hybrid technology, qualified to standard military specification, was modified both in materials and fabrication processes to achieve this high-temperature operation. In addition to documenting this Sandia-developed technology, various alternate approaches are described to increase the versatility and applicability of these methods.

HIGH TEMPERATURE HYBRIDS FOR USE UP TO 275°C -- DRIFT AND LIFETIME, A. F. Veneruso, D. W. Palmer, Sandia National Laboratories and M. G. Reagan, Teledyne Philbrick, Proceedings of 1980 International Microelectronics Symposium, International Society for Hybrid Microelectronics, October 20-22, 1980, New York, New York.

This paper reviews the drift and lifetime performance of 275°C hybrid microcircuits that were recently developed by Teledyne Philbrick and Sandia National Laboratories. The specific technology employed is based on temperature tolerant thick films and discrete silicon JFETs. The results of high temperature circuit testing are reviewed; component and circuit degradation and failure modes are described and compared to predictions; and finally, design rules are given to maximize lifetimes and to minimize performance drift for up to 10,000 hours of operation at 275°C. Although these circuits were developed for instrumenting geothermal boreholes, many other applications for this technology exist in such areas as fossil fuel exploration and production systems, jet engine monitors, and nuclear reactor monitors.

THE FRONTIERS OF HIGH TEMPERATURE ELECTRONICS, A. F. Veneruso and R. C. Heckman, Sandia National Laboratories, Components, Hybrids, and Manufacturing Society Newsletter, January 1981, New York, New York.

This paper provides an overview of contemporary high-temperature electronics that can operate beyond the conventional 125°C limit. The needs and applications for this technology in such vital areas as oil, gas, and geothermal downhole instrumentation are reviewed. The state-of-the-art of components and circuits is then presented along with a specific design example of a 275°C voltage regulator. Finally, the direction of future R&D is discussed.

D. Interconnections

ALUMINUM WIRE TO THICK-FILM CONNECTIONS FOR HIGH-TEMPERATURE OPERATION, D. W. Palmer, F. P. Ganyard, Sandia National Laboratories, IEEE Trans. on Components, Hybrids, and Mfg. Technology, Vol. CHMT-1, No. 3, September 1978.

Hybrid microcircuits in geothermal instrumentation must operate from room temperature to 300°C. Bond failure occurred during operation of initial geothermal circuits due to intermetallic growth at the aluminum wire-to-gold conductor interface. To remedy this problem, two wire bonding techniques have been qualified in high-temperature aging tests: 1) ultrasonic bonding of aluminum wire directly to modified fritless gold conductor inks (DuPont 9910, AVX 3520, and TFS A328) and 2) insertion of a 1 mil diffusion barrier pad between the thick film and the aluminum wire. Both systems allow 100-1000 hours operation at 300°C. Three alloys of wire were tested: pure aluminum, aluminum with 1 percent silicon, and aluminum with 1 percent magnesium. The degradation rates differed greatly with pure aluminum being the least tolerant to temperature aging and wire with 1 percent silicon faring best. Because thick-film surfaces tend to be harder than thin-film surfaces, hardened aluminum wire (elongation 0.5 percent) formed bonds with less pad deformation and, consequently, with higher pull strengths than standard bonding wire (elongation 1-3 percent). Comparison of wire bonds aged at three temperatures wire (elongation 1-3 percent). Comparison of wire bonds aged at three temperatures (250, 300, and 350°C) demonstrated several orders of magnitude spread in degradation rates; for 1000 h bond lifetime, 300°C was found to be about the highest allowed operational temperature for direct bonding to gold. Disks of kovar and nickel of 1-mil thickness and 30 mils diameter were used as diffusion barriers between the gold and aluminum. Evaporated on one side of each disk was a 1 micrometer gold thin film for thermocompression bonding to the thick film; the other side received an evaporated aluminum film for wire bonding. Aging for 1000 h up to 350°C produced no increase in bond resistance for any of the three wire alloys tested. Some decrease in pull strength with time was noticed but was attributed to anealing of the wire.

CABLEHEAD ASSEMBLY FOR HOSTILE ENVIRONMENT WELL LOGGING, Joe Allen Coquat, Sandia National Laboratories, Geothermal Resources Council, Transactions, Vol. 3, September 1979, p. 133.

One of the most challenging problems in geothermal logging is to develop a cablehead that interconnects the wireline cable to the downhole instrument such that the system will successfully operate in a geothermal well. A high temperature (275°C), corrosion resistant logging cablehead for use with single conductor cables is described. The head has demonstrated the ability to solve electrical communications problems (leakage resistance) generally associated with the cable-to-sonde interface while logging hostile environment geothermal wells.

E. Materials

EVALUATION OF SEALS FOR A GEOTHERMAL LOGGING TOOL, Charles Arnold, Jr., Joseph A. Coquat, Leonard E. Baker, Geothermal Resources Council, Transactions, Vol. 2, July 1978, p. 17.

The seal efficiency and environmental resistance of various elastomeric o-rings and a metallic joint that were immersed in geothermal brine of water at elevated temperatures and pressures were determined. A leakproof seal was maintained with a stainless steel Conoseal-joint for 100 hours in water and 24 hours in geothermal brine at 275°C and 34.5 MPa (5000 psi). Only very small quantities of moisture penetrated o-ring seals made from Kalrez, a perfluoroelastomer, ethylene/propylene rubber and a Parylene C coated Viton o-ring. All other rubber seals failed catastrophically.

DEGRADATION OF ELASTOMERS IN GEOTHERMAL BRINE AT ELEVATED TEMPERATURES AND PRESSURES, C. Arnold and J. A. Coquat, Sandia National Laboratories, Abstracts of papers of the American Chemical Society, Vol. 1979, p. 132, April 1979.

Elastomeric seals are required in logging tools for geothermal sondes to protect the internal electronic circuitry from moisture as the tool is lowered into a borehole. The stability of five generic classes of elastomers toward geothermal brine at 275°C/5000 psig for 24 hours was determined in order to identify those elastomers which could be used for such purposes. The five classes of rubbers evaluated were perfluoro-elastomers, fluoroelastomers, hydrocarbons, nitriles and silicones. Stability was determined by visual examination and by measuring the changes that occurred in the tensile properties of the rubber as a result of exposure. In addition, changes in the glass transition temperature of the elastomer were determined. The highest stability was noted for a perfluoroelastomer that contained both asbestos and carbon black fillers. Even so, this elastomer suffered a 24% loss in its tensile strength as a result of exposure. The least stable elastomer was the silicone; this elastomer underwent hydrolytic reversion with complete loss of physical integrity. The nitrile rubber also exhibited rather poor stability; the glass transition temperature of this elastomer increased markedly and the rubber became so brittle that tensile properties could not be determined. Intermediate stability was noted for the fluoroelastomers and hydrocarbon types. The observed property changes can be rationalized by postulating structural changes on a molecular level which involve both chain scission and cross-linking. Infrared analysis of the pyrolysis products of the fluoroelastomer suggests that dehydrofluorination of the backbone is also one of the degradation reactions.

FACTORS INFLUENCING THE SELECTION OF CORROSION-RESISTANT ALLOYS FOR HIGH-TEMPERATURE, DOWNHOLE APPLICATIONS, David L. Douglass, UCLA, under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 143, SAND80-0834.

The environment existing downhole for both petroleum and geothermal systems is highly corrosive and generally contains oxygen, sulfur, and chlorine, among other species. These three elements are particularly corrosive, either singularly or in combination. Basically, the problem

is designing against the troublesome effect of corrosive agents. The most important consideration in selecting an alloy for a particular application is to define the environment in terms of gas or liquid composition, temperature, and pressure. This task may be difficult, if not impossible, to do. However, if we assume that the environment can be determined, there are numerous factors that determine which alloy might survive for the desired lifetime. For example, if the system is liquid rather than gaseous, careful thought must be given to localized corrosion as well as to general corrosion. Such phenomena as pitting, waterline corrosion, stress corrosion cracking (SCC), intergranular corrosion, etc., must be considered. These phenomena might mitigate against using an alloy whose general corrosion rate was more than adequate. Likewise, gaseous systems require different alloys, depending on the gas composition. Each case must be considered individually; it is dangerous to make generalizations. This paper will discuss some of the factors involved in the various forms of corrosion and show the rationale involved in selecting the right material for a given application.

SEARCH FOR HIGH TEMPERATURE TRANSFORMER MATERIALS, R. K. Pandey and M. H. Weichold, Texas A&M University under contract to Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 133, SAND80-0834.

The worldwide scarcity of petroleum has warranted a vigorous search for other sources of energy. Like nuclear and solar energies, it is anticipated that geothermal energy will play a significant role in meeting the accelerating demands of energy. According to the USGS it is possible that by 1990 about 10 GW of electricity will be made available in the USA by geothermal sources. In order to achieve this goal, new technologies have to be developed which would reduce drilling costs and provide means to monitor the geothermal boreholes reliably. Since the temperature of a geothermal well varies significantly with its depth -- for example, it is about 300°C at 3 km and about 400°C at 4 km -- the logging instruments must have components which can operate reliably at elevated temperatures. Logging tools available currently are mostly those which are suitable for the oil and gas industry. They operate efficiently only up to 180°C; their reliability and life expectancy is reduced substantially above 180°C. Therefore, there is a need to develop electronic and magnetic components capable of operating between 200 to 400°C. Furthermore, they must be able to withstand severe environmental conditions of a geothermal well.

HIGH TEMPERATURE METALLIZATION SYSTEM FOR SOLAR CELLS AND GEOTHERMAL PROBES, J. D. Wiley, J. H. Perepezko, J. E. Nordman, University of Wisconsin under contract to Sandia National Laboratories, SAND80-7167, December 1980.

Amorphous films of the alloys Ni-Nb, Ni-Mo, W-Si, and Mo-Si were deposited on semiconducting substrates by RF sputtering from composite cathodes. The films adhere extremely well to Si, GaAs, and GaP during and after thermal cycling from -200°C to at least 500°C. All films investigated to date have remained amorphous during 1 hour anneals at 500°C, and some alloy compositions have been found which remain amorphous after annealing at $\geq$ 575°C. Rutherford backscatter analysis has been used to study the diffusion of Au in amorphous Ni-Nb. We find $D < 10^{-18}$ cm^2 at 450°C. Additional diffusion studies have been

performed using Auger profilling. Initial results show that amorphous Ni-Nb and W-Si may be excellent diffusion barriers against Cu and Au, respectively, at temperatures $\leq$ 500°C.

F. Miscellaneous

INSTRUMENTATION FOR EARTH RESOURCES EXTRACTION, SAND79-0522, D. A. Northrop, A. F. Veneruso, Sandia National Laboratories, May 1979, Sandia Technology, R. J. Lawrence and P. L. Mead, Editors.

The needs of geothermal technology focused upon the development of high-temperature instrumentation hardware and the development of fossil-energy extraction technologies requiring field-oriented instrumentation efforts aimed at characterization and understanding of in situ processes are described.

STANDARDIZATION TO ACCELERATE THE DEVELOPMENT AND USE OF GEOTHERMAL LOGGING INSTRUMENTATION, Anthony F. Veneruso, Sandia National Laboratories, Sandardization News, Vol. 7, No. 10, October 1979, p. 29. American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA, 19103.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities (∿ 180°C) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging Instrumentation Development Program being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy (DGE) is an industry-based effort to develop and apply the high-temperature instrumentation needed to make geothermal borehole measurements. The near-term goal is to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7000 psi); subsequent goals are to extend the capabilities to 350°C and 138 MPa (20,000 psi). Working closely with geothermal producers, logging service companies are conducting research and development to correct technical deficiencies so they may adequately serve the growing geothermal market. The basic impediments they face involve special technologies that are not normally required in their trade and for which there are insufficient incentives to develop. It is precisely those technologies that are being developed by the logging instrumentation program.

GEOTHERMAL ENERGY RESOURCES AND UTILIZATION, SAND78-0138, A. F. Veneruso, Proceedings -- Institute of Environmental Sciences, 940 East Northwest Highway, Mount Prospect, Illinois 60056.

Geothermal energy is obtained from naturally generated heat within the earth. This heat is thought to result from the radioactive decay of naturally occurring radioisotopes deep within the earth's crust. Certain geologic formations create significant concentrations of this heat and give rise to surface manifestations such as hot springs and geysers. These areas have been used since ancient times for recreational and medical purposes. Today geothermal energy is a vast potential source of useful power which, although highly site specific, should become available for a wide variety of important applications. Although a particular reservoir may be depleted after several decades of use, the overall supply is virtually inexhaustible.

G. Program Reviews/Summaries

GEOTHERMAL LOGGING INSTRUMENTATION DEVELOPMENT PROGRAM PLAN, SAND78-0316, A. F. Veneruso, J. Polito, and R. C. Heckman, Sandia National Laboratories, August 1978.

This Geothermal Logging Instrumentation Development Program Plan outlines a nine-year, industry-based program to develop and apply high temperature instrumentation technology which is needed by the borehole logging industry to serve the rapidly expanding geothermal market. Specifically, this program will upgrade existing materials and sondes to improve their high-temperature reliability. To achieve this goal, specialized equipment such as high temperature electronics, cables and devices for measuring formation temperature, flow rate, downhole pressure, and fractures will be developed. In order to satisfy critical existing needs, the near-term (FY-80) goal is for operation at or above 275°C in pressures up to 48.3 MPa (7,000 psi). The long-term (FY-84) goal is for operation up to 350°C and 138 MPa (20,000 psi). This program plan has been prepared for the Department of Energy's Division of Geothermal Energy (DGE) and is a portion of the DGE Long-Range Geothermal Well Technology Program.

GEOTHERMAL LOGGING INSTRUMENTATION, SAND78-1142, A. F. Veneruso, J. A. Coquat, Sandia National Laboratories, Proceedings of MIDCON/78 Conference, Dallas, Texas, December 12-14, 1978.

This paper describes the progress and plans of the Geothermal Logging Instrumentation Development Program being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy. This is an industry-based program to develop and apply the high temperature instrumentation needed to make geothermal borehole measurements. Specifically, this program is upgrading existing materials and sondes for improved high temperature performance, as well as developing component technology such as high temperature cables and electronics to make measurements such as formation temperature, flow rate and high resolution downhole pressure. In order to satisfy critical existing needs, the near-term goal is for operation at 275°C and 48.3 MPA (7000 psi) by the end of FY-80. The long-term goal is for operation up to 350°C and 138 MPa (20,000 psi) by the end of FY-84.

TECHNOLOGY DEVELOPMENT FOR HIGH TEMPERATURE LOGGING TOOLS, SAND79-0013, A. F. Veneruso and J. A. Coquat, Sandia National Laboratories, Transactions of 20th Annual Logging Symposium, Tulsa, Oklahoma, June 3-6, 1979, Society of Professional Well Log Analysts.

A set of prototype, high temperature logging tools (temperature, pressure, and flow) were tested successfully to temperatures up to 275°C in a Union geothermal well in northern New Mexico during November 1978 as part of the Geothermal Logging Instrumentation Development Program. This program is being conducted by Sandia Laboratories for the Department of Energy's Division of Geothermal Energy. This paper describes the progress and plans for this industry-based program to develop and apply the high temperature instrumentation technology needed to make reliable geothermal borehole measurements. Specifically, this program is upgrading existing sondes for improved high temperature performance, as well as applying new materials (elastomers, polymers, metals and ceramics) and developing component technology such as high

temperature cables, cable-heads and electronics to make borehole measurements such as formation temperature, flow rate, high resolution pressure and fracture mapping. In order to satisfy critical existing needs, the near-term goal is for operation up to 275°C and 7000 psi by the end of FY-80. The long-term goal is for operation up to 350°C and 20,000 psi by the end of FY-84.

A PERCEPTION OF THE GEOTHERMAL INDUSTRY, A. F. Veneruso, Sandia National Laboratories, Proceedings of Publication Invitation to the October 1979 Organizational Meeting for Geothermal Energy Standards, ASTM Headquarters, Philadelphia, Pennsylvania.

One of the primary beneficiaries of appropriate geothermal standards is that fledgling industrial structure that we refer to as the U.S. Geothermal Industry. What makes up this structure, how can it benefit from standards, and how can it participate in setting up those standards?

HIGH TEMPERATURE INSTRUMENTATION DEVELOPMENT AND COMMERCIALIZATION FOR GEOTHERMAL APPLICATIONS, A. F. Veneruso, H. M. Stoller, Sandia National Laboratories, Geothermal Resources Council, Transactions, Vol. 3, September 1979, p. 745.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities ($\sim$ 180°C) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging Instrumentation Development Program is being conducted by Sandia Laboratories for the Division of Geothermal Energy (DOE/DGE). This program emphasizes the development and field test performance verification of severe environment components such as 275°C electronics, high temperature-high resolution pressure transducers, elastomeric and metal tool seals, cableheads, and cables. Since the report to the GRC last year, a number of these essential developments have come to fruition: a set of prototype geothermal logging tools (temperature, pressure, and flow), cables, and cableheads were successfully field tested to temperatures up to 275°C in a geothermal well during November 1978; an experimental high resolution quartz pressure transducer was successfully tested up to 275°C and 1000 psi; a gallium phosphide diode was developed and found to operate successfully up to 400°C; and the mechanical clocks in the Amerada gauge were upgraded in temperature and reliability.

HIGH TEMPERATURE ELECTRONICS FOR GEOTHERMAL ENERGY, SAND79-1524, A. F. Veneruso, Sandia National Laboratories, IEEE Circuits and Systems Magazine, Vol. 1, No. 3, September 1979.

The worldwide production of electric power from geothermal energy sources at present is 1.2 GW. The largest facility is in the United States at The Geysers, in northern California, where 605 MW is on-line. Recent estimates indicate that geothermal energy sources could produce over 10 GW of power in the USA by 1990; however, to achieve this goal there must be accelerated exploration and development. Developers and investors may be reluctant to make the necessary commitments if there is a high risk of uncertainty in a geothermal reservoir's production potential. Also, once a system is in operation, engineers periodically need accurate and timely downhole information from each well in order

to obtain production. Instrumentation for geothermal borehole measurements is being expanded beyond today's limited capabilities. Prototypical logging tools have been successfully field-tested to 275°C; a high-resolution quartz pressure transducer and a gallium phosphide diode have been successfully tested. Near-term goals of current programs are to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7,000 psi).

HIGH TEMPERATURE TECHNOLOGY -- POTENTIAL, PROMISE, AND PAYOFF, A. F. Veneruso, Sandia National Laboratories, Proceedings of High Temperature Electronics and Instrumentation Seminar, December 1979, Houston, Texas, p. 17, SAND80-0834.

The purpose of this two-day seminar is to review the state-of-the-art and the recent substantial progress in High Temperature Electronics and Instrumentation. This seminar comes at a critical time and it addresses a vital subject. The frontiers of technology are rapidly moving beyond the conventional 125°C boundary. Already, special "hostile environment" instruments routinely operate up to 180°C, a few prototype systems have been field tested for 275°C, new development is underway for 300°C integrated circuits, and research continues on components up to 500°C.

THE NATIONAL GEOTHERMAL EXPLORATION TECHNOLOGY PROGRAM, L. Ball, and J. W. Salisbury, Department of Energy, P. R. Kintzinger, Los Alamos Scientific Laboratories, A. F. Veneruso, Sandia National Laboratories, and S. H. Ward, University of Utah, Geophysics, Vol. 44, No. 10 (October 1979); pp 1721-1737.

In response to the Geothermal Energy Research, Development, and Demonstration Act of 1974, a federal geothermal program has been established with the objective of stimulating the commercial development of geothermal resources. The program goal is to increase the annual rate of energy utilization from the present 0.04 quads (500 MWe) to 0.3-0.5 quads in the near term (about 1985), 4.0-9.0 quads in the mid-term (1985-2000), and 16.0-28.0 quads in the long term (by about 2020). The realization of these goals depends upon the discovery and exploitation of many new geothermal resource areas.

The Department of Energy program for geothermal exploration and assessment has been structured to address technological barriers presently hindering the economical discovery and delineation of geothermal resources. We describe the program elements -- exploration technology, reservoir assessment, reservoir confirmation, and reservoir engineering -- in light of the need to evaluate some 1500 new prospects in order to meet the federal midterm electric power goal of 20,000 MWe on-line by the year 2000.

HIGH TEMPERATURE GEOTHERMAL LOGGING INSTRUMENTATION, Bruce H. Major, SAND80-1676J, Proceedings of Scale Control Workshop, Los Alamos Scientific Laboratories, April 1980, Los Alamos, New Mexico.

Instrumentation for making geothermal borehole measurements is limited by the temperature capabilities ($\sim$ 180°C) of existing logging equipment developed for the oil and gas industry. The Geothermal Logging

Instrumentation Development Program being conducted by Sandia National Laboratories for the Department of Energy's Division of Geothermal Energy is an industry-based effort to develop and apply the high temperature instrumentation needed to make geothermal borehole measurements. This program emphasizes the development and field test performance verification of severe environment components such as 275°C electronics, high temperature-high resolution pressure transducers, elastomeric and metal tool seals, cableheads, and cables. Instrumentation for geothermal borehole measurements is being expanded beyond today's limited capabilities. Prototype logging tools have been successfully field tested to 275°C; a high resolution quartz pressure transducer and a gallium phosphide diode have been successfully tested. Near-term goals of current programs are to develop instrumentation for use at 275°C in pressures up to 48.3 MPa (7,000 psi).

GEOTHERMAL LOGGING INSTRUMENTATION DEVELOPMENT, Electronic Packaging and Production Magazine, P. A. Bonn, Sandia National Laboratories, International Society for Hybrid Microelectronics, October 20-22, 1980, New York, available from Microelectronic Manufacturing and Testing, P. O. Box 159, 700 Peterson Road, Libertyville, Illinois 60048.

This exhibit displays electronic components, thick-film hybrid microcircuitry, transducers, and complete prototype tools that have been developed and field tested to 282°C in a geothermal well. This continuing development expands the capability of geothermal instrumentation as part of a national program conducted by Sandia National Laboratories for the Department of Energy's Division of Geothermal Energy. The transfer of high-temperature technology to the marketplace in order to stimulate further development and application has been accomplished through a contract with Teledyne Philbrick-Boston.

DETECTION, DIAGNOSIS AND PROGNOSIS IN GEOTHERMAL WELL TECHNOLOGY, A. F. Veneruso, H. Chang, Sandia National Laboratories, Proceedings of 32nd Meeting of the Mechanical Failures Prevention Group, NBS, October 7-9, 1980, Santa Monica, California.

For successful and safe operation of a geothermal well, the condition of the casing and cement must be accurately determined. Measurements on casing wall thickness, corrosion damage, holes, cracks, splits, etc., are needed to assess casing integrity. Cement bond logs are needed to detect channels or water pockets in cement behind pipe and to determine the state of the cement bond to the pipe and formation. Instrumentation for making such measurements is limited by the temperature capabilities (< 175°C) of existing logging equipment developed for the oil and gas industry. This paper reviews the instruments that are needed for geothermal casing and cementing inspection, identifies the principle deficiencies in their high temperature use, and describes Sandia's upgrade research program on multi-arm caliper and acoustic cement bond logging tool. The key electronic section in a multi-arm caliper will consist of 275°C circuits designed by Sandia. In an acoustic cement bond logging tool, a simple circuit with possibilities of using commercially available components for high temperature operation is being developed. These new tools will be field tested for operation at a minimum temperature of 275°C and pressure of 7000 psi for up to 1000 hours.

III. 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 Department of Energy, 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.

The initial proposal by Sandia National Laboratories to investigate the extraction of thermal energy from buried molten rock deposits was put forward in mid-1973. From that proposal, investigative studies on a small scale were begun under discretionary funding. This level of effort was continued until mid-1974, when the initial funding for the project (at that time called Magma Tap) was received from the AEC (now DOE) Division of Physical Research (now Division of Basic Energy Sciences). Activities to accomplish the objective are divided into the following five tasks: 1) Resource Location and Identification, 2) Source Tapping, 3) Magma Chracterization, 4) Materials Compatibility, and 5) Energy Extraction.

A. Source Location and Definition

SUMMARY OF RESULTS FROM ELECTROMAGNETIC AND GALVANIC SOUNDS ON KILAUEA IKI LAVA LAKE, HAWAII, B. D. Smith, C. J. Zablocki, F. Frischknect, and V. J. Flanigan, USGS Open File Report 77-59, 1977.

The purpose of this report is to summarize various electrical sounding studies made on the Kilauea Iki lava lake and to present some of the preliminary interpretations that resulted from the measurements. The following discussion is not intended as a complete interpretation, but is intended to summarize the major points made in an invited oral presentation at the American Geophysical Union Fall Meeting held in San Francisco, California, on December 6, 1976. This paper was part of a group of papers dealing with various geophysical studies recently made on the Kilauea Iki lava lake.

FINE-MESH PASSIVE SEISMIC SURVEY OF KILAUEA IKI LAVA LAKE, J. L. Colp, Sandia National Laboratories, EOS Trans., Am. Geophys. Union, V. 58, No. 5, p. 311, May 1977.

A fine-mesh passive seismic survey of Kilauea Iki lava lake was conducted as a follow-on to an earlier program of mapping of thermal cracks. The objective of the fine-mesh survey was to delineate more sharply the edge of the buried molten lava lense. The seismic array consisted of six vertical motion geophones located fifty feet (15 m) apart. This array was moved to a number of locations in the northeast quadrant of Kilauea Iki. Data recorded during forty minute long observations indicated that discrete signals from single thermal cracks could be observed. Data analysis gives a clear picture of the edge of the molten lense based on the markedly increased number of thermal crack events observed. Confirmation of the validity of these observations awaits the planned drilling program.

UPMELTING IN MAGMA BODIES, H. C. Hardee, D. W. Larson, Sandia National Laboratories, A. Herschman, Editor, Am. Assoc. Adv. Sci., Washington, DC, p. 11, 1978, Proceedings of AAAS 144th National Meeting, Washington, DC, February 12-17, 1978.

Analytical and numerical heat transfer calculations are used to show that upward melting magma systems tend to be approximately equidimensional with height to width ratios limited to around seven or less. This agrees with observations on the magma body beneath Yellowstone which appears to have a height/width ratio of five. Experiments run in the laboratory with model simulants such as paraffin also confirm the predictions. Injected magmas with very high height/width ratios appear to be formed by a forced convection process which involves little, if any, melting or natural convection.

SURFACE HEAT FLUX DISTRIBUTION ABOVE MAGMA SOURCES, H. C. Hardee, D. W. Larson, Sandia National Laboratories, A. Herschman, Editor, Am. Assoc. Adv. Sci., Washington, DC, p. 111, 1978, Proceedings of 144th National Meeting, Washington, DC, February 12-17, 1978.

Analytical heat transfer techniques are used to calculate the surface heat flux distribution above rectangular (dikes) and spherical magma

sources. The solutions are concerned primarily with steady-state effects in a conduction dominant region overlying the magma body. Transient effects are included for the spherical case. This study has application in the location of magma bodies. The surface heat flux distributions can be used to estimate characteristics of the magma body such as extent of the body and depth.

A LAVA LAKE GEOPHYSICAL SENSING EXPERIMENT, J. L. Colp, Sandia National Laboratories, Transactions, American Geophysical Union, Vol. 59, No. 4, pp 311-312, 1978, AGU 1978 Spring Meeting, April 17-21, 1978, Miami Beach, Florida.

For the past four years, Sandia Laboratories has been performing a Department of Energy sponsored project to assess the scientific feasibility of extracting energy directly from buried circulating magma sources. One of the tasks of this project is that of the development, demonstration, and verification of exploratory techniques for locating and defining buried molten rock sources. In March 1975, a workshop co-sponsored by Sandia Laboratories and the U. S. Geological Survey with about thirty scientists was convened to assess the present state of knowledge on studies on magma and to recommend critical needs for research. A major recommendation of this group was to evaluate geophysical techniques over a "known" molten rock body such as Kilauea Iki lava lake in Hawaii. During early 1976, a Lava Lake Sensing Experiment at Kilauea Iki was sponsored by Sandia Laboratories. Active and passive seismic surveys were performed by experimentors from Massachusetts Institute of Technology, Prof. Keitii Aki, Principal Investigator. Resistivity and active electromagnetic surveys were run by experimentors from the USGS Denver office and the Hawaiian Volcano Observatory, Dr. Frank Frischknect, Principal Investigator, Audio-magnetotelluric survey methods were used by the University of Texas scientists, Prof. Francis Bostick, Principal Investigator. A supplemental fine mesh passive and active downhole seismic surveys were performed by Sandia National Laboratories personnel.

SUMMARY OF GEOPHYSICAL SENSING EXPERIMENTS ON KILAUEA IKI LAVA LAKE, SAND78-0240A, J. Hermance, D. W. Forsythe, Brown University, and J. L. Colp, Sandia National Laboratories, Proceedings of American Geophysical Society Spring Meeting, April 17-21, 1978, Miami Beach, Florida, EOS, Am. Geophys. Union Trans. Vol. 59, No. 4, p. 312, 1978.

The Hawaiian lava lake in the Kilauea Iki pit crater, resulting from the 1959 summit eruption of Kilauea Volcano, has served as a natural laboratory for the continuing study of the petrology, rheology and thermal history of ponded molten basalt flows in the actual field environment. During 1975 and 1976, a series of electromagnetic and seismic experiments was coordinated, and in some cases, supported by the Magma Energy Program at Sandia National Laboratories in an attempt to define the in-situ geophysical properties and the configuration of the molten lava core as closely as possible. This effort involved workers from the USGS, University of Texas, MIT, Sandia National Laboratories, and Brown University. Studies to date indicate that the present lake has a cool, resistive surface layer, under-saturated with water to a depth of 5 m. A warm, wet layer containing appreciable water and/or steam is essentially isothermal (100°C) to 33 m. From 33 to 45 m the temperature climbs rapidly (100-1070°C) until one encounters a thin plexus of molten sills interbedded with solid layers. Below this (50 m) one finds a truly molten layer having the highest

temperature, lowest viscosity and lowest density of olivine phenocrysts. At 70 m one encounters a transition zone to a crystal-line mush, and finally (between 80 and 95 m) solid basalt extending down to the pre-flow surface at a depth of 115 to 120 m.

SEISMIC PROPERTIES OF A SHALLOW MAGMA RESERVOIR IN KILAUEA IKI BY ACTIVE AND PASSIVE EXPERIMENTS, K. Aki, B. Chouet, M. Fehler, G. Zandt, R. Koyanagi, J. Colp, R. G. Hay, Journal of Geophysical Research, Vol. 83, No. 85, pp 2273-2282, May 10, 1978

The use of multiple methods is essential for determination of seismic properties of a complex structure like a partially frozen lava pond. In our experiment with Kilauea Iki during March 1976, 1) the spatial distribution of seismic events originating from the crust best defined the lateral location of the magma lens, 2) the S waves transmitted through the magma lens and dispersion of love waves generated by explosive sources in the Iki floor constrained the S wave velocity structure, and 3) P waves from explosions revealed an extremely low P velocity zone below the crust. From love and S wave data we infer a rather thin (less than 10 m) magma lens, which, in response to our weak seismic signal, behaves like a viscous liquid with apparent viscosity of about 10^7 P and apparent shear velocity of about 0.2 km/s. Apparent high viscosity at low stress level was reported by Shaw, et al., (1968), who made an in situ measurement of viscosity at Makaopuhi, Hawaii, and attributed its possible source to the presence of vesicles. Liquid containing vesicles apparently behaves like a bingham body: a solid below the liquid above a threshold stress. The presence of vesicles of a few volume percent in the melt can also reduce the apparent bulk modulus to as low as the apparent rigidity inferred from love and S wave data. The P velocity of about 0.3 km/s is possible in the melt with 5% vesicles. The observed refraction data require the P velocity in the lower crust to be as low as 0.9 km/s. This low velocity may be attributed to dry cracks unfilled with liquid magma.

A CRITICAL ASSESSMENT OF GEOPHYSICAL SENSING EXPERIMENTS ON KILAUEA IKI LAVA LAKE, SAND77-0828, J. F. Hermance, D. W. Forsythe, and J. L. Colp, Sandia National Laboratories.

The Hawaiian lava lake in the Kilauea Iki pit crater, resulting from the 1959 summit eruption of Kilauea volcano, has served as a natural laboratory for the continuing study of the petrology, rheology, and thermal history of ponded molten basalt flows in the field environment. During 1975 and 1976, a series of electromagnetic and seismic experiments were coordinated, and in some cases supported, by the Magma Energy Program at Sandia National Laboratories in an attempt to define the in-situ geophysical properties and the configuration of the molten lava core as closely as possible. This effort involved workers from the United States Geological Survey (USGS), University of Texas, Massachusetts Institute of Technology (MIT), Sandia National Laboratories, and Brown University. Drilling and geophysical experiments in 1976 suggested that the solidified crust of the lava lake had a cool, resistive surface layer, undersaturated with water to a depth of 5 metres. A warm, wet layer containing appreciable water and/or steam was essentially isothermal (100°C) to 33 metres. From 33 to 45 metres the temperature climbed rapidly (from 100 to 1,070°C) until a thin plexus of molten sills was encountered, interbedded with solid layers. Below this (50 metres) was apparently a layer having the highest temperature, lowest viscosity,

and lowest density of olivine phenocrysts. At 70 metres, a transition zone to a crystalline mush was indicated, and finally (between 80 and 95 metres), solid basalt extended down to the preflow surface at a depth of 115 to 120 metres.

SUMMARY OF GEOPHYSICAL SENSING EXPERIMENTS ON KILAUEA IKI LAVA LAKE, J. F. Hermance, D. W. Forsythe, Brown University, and J. L. Colp, Sandia National Laboratories, Proceedings, Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 1979.

The Hawaiian lava lake in the Kilauea Iki pit crater, resulting from the 1959 summit eruption of Kilauea Volcano, has served as a natural laboratory for the continuing study of the petrology, rheology and thermal history of ponded molten basalt flows in the actual field environment. During 1975 and 1976, a series of electromagnetic and seismic experiments were coordinated, and in some cases supported, by the Magma Energy Program at Sandia Laboratories in an attempt to define the in-situ geophysical properties and the configuration of the molten lava core as closely as possible. This effort involved workers from the USGS, University of Texas, MIT, Sandia Labs and Brown University. Drilling and geophysical experiments in 1976 suggested that the solidified crust of the lava lake had a cool, resistive surface layer, undersaturated with water to a depth of 5 m. A warm, wet layer containing appreciable water and/or steam was essentially isothermal (100°C) to 33 m. From 33 to 45 m the temperature climbed rapidly (100-1070°C) until a thin plexus of molten sills was encountered, interbedded with solid layers. Below this (50 m) was apparently a layer having the highest temperature, lowest viscosity and lowest density of olivine phenocrysts. At 70 m a transition zone to a crystalline mush was indicated and finally (between 80 and 95 m) solid basalt extending down to the pre-flow surface at a depth of 115 to 120 m. Drilling in 1978/79 confirmed the basic elements of this model, in particular the existence of the crystalline mush. The thickness of the molten layer having a low concentration of olivine phenocrysts may have been previously overestimated somewhat.

THERMAL TECHNIQUES FOR CHARACTERIZING MAGMA BODY GEOMETRIES, H. C. Hardee, D. W. Larson, Geothermics International Journal of Geothermal Research and Its Applications, Vol. 9, No. 3-4, p. 237 (1980).

The surface heat flux distribution resulting from emplaced magma bodies can be used to help characterize the magma source. Closed-form analytical solutions for the conduction heat transfer from various idealized magma geometries (dikes, sills, and spheres) are obtained using either the Schwarz-Christoffel transformation theorem (dikes and sills) or the "method of images" with superposition (spheres). Comparison of these analytically determined heat flux distributions with field data from active geothermal areas at Yellowstone, Avachinsky Volcano, Kilauea Iki, and the Coso geothermal area indicates that these fields may be conduction dominant, at least over certain depths. The comparison for Yellowstone implies that a sharp thermal boundary exists at a depth of approximately 1 km; this supports the suggestion by Morgan, et al., (1977) that a strong hydrothermal zone exists at about that depth. The comparison for Avachinsky indicates that a spherical magma chamber exists at approximately 4-8 km depth; this is in close agreement with estimates by Fedotov, et al., (1976) for a spherical magma chamber at 5 km depth. The comparison for Kilauea Iki indicates that the edge of the buried molten lava lense was 210-216 m from the center of the lake in 1975; this result is in good agreement with several independent geophysical measurements.

THERMAL TECHNIQUES FOR LOCATING AND CHARACTERIZING BURIED MAGMA BODIES, H. C. Hardee and D. W. Larson, Sandia National Laboratories, Hawaii Symposium Proceedings on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16-22, 1979.

The surface heat flux distribution resulting from emplaced magma bodies can be used to help characterize the magma source. Closed-form analytical solutions for the heat transfer from various idealized magma geometries (dikes, sills, and spheres) are obtained using either the Schwarz-Christoffel transformation or the "method of images." Comparison of these analytically determined heat flux distributions with field data from active geothermal areas at Yellowstone, Avachinsky volcano, Kilauea Iki, and the Coso geothermal area indicates that these fields may be conduction dominant, at least over certain depths. The Yellowstone comparison indicates that the top of a convecting hydrothermal zone exists at a depth of around 1 km and this agrees with the findings of other investigators who base their conclusion on seismic and drilling data. The Avachinsky comparison indicates that a magma chamber exists at a depth of 4.8 km and this agrees with estimates by Sergey Fedatov for a spheroidal magma chamber at 5 km depth.

TEMPERATURE MEASUREMENTS IN THE CRUST OF KILAUEA IKI LAVA LAKE, H. C. Hardee, Sandia National Laboratories, Proceedings of Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16-22, 1979.

The crust of Kilauea Iki lava lake currently consists of an upper porous two-phase convection zone 41 m thick and a lower conduction zone 12 m thick extending to the melt. The crust has been solidifying at a near constant rate of 6.7×10^{-8} m/s for the past twelve years. The thickness of the lower conduction zone has been relatively constant during this period. Temperature profiles in the lower conduction zone have a curvature that can be explained in terms of a moving solidification-front conduction solution. Recent temperature profiles show the predicted reversal of curvature where solidification has ceased.

COMPARATIVE ASSESSMENT OF FIVE POTENTIAL SITES FOR HYDROTHERMAL-MAGMA SYSTEMS: SUMMARY, DOE/TIC-11303, November 1980.

An objective of the Thermal Regimes portion of the Continental Scientific Drilling Program (CSDP) is the development of a fundamental understanding of energy transport within and between hydrothermal and magma systems. A comparative assessment of five potential hydrothermal-magma sites for this facet of the Thermal Regimes part of the CSDP has been prepared for the DOE Office of Basic Energy Sciences. Four DOE laboratories (Los Alamos National Laboratory, Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory, and Sandia National Laboratories) participated in this study. The five sites are: The Geysers-Clear Lake, California; Long Valley, California, Rio Grande Rift, New Mexico; Roosevelt Hot Springs, Utah; and Salton Trough, California. This site assessment study has drawn together background information (geology, geochemistry, geophysics, and energy transport) on the five sites as a preliminary stage to site selection. Criteria for site selection are that potential sites have identifiable, or likely, hydrothermal systems and associated magma sources, and that important scientific questions can be identified and answered by deep scientific holes.

COMPARATIVE ASSESSMENT OF FIVE POTENTIAL SITES FOR HYDROTHERMAL-MAGMA SYSTEMS: ENERGY TRANSPORT, SAND80-1671, Harry C. Hardee, Sandia National Laboratories, November 1980.

A comparative assessment of five sites is being prepared as part of a Continental Scientific Drilling Program (CSDP) review of thermal regimes for the purpose of scoping areas for future research and drilling activities. This background report discusses the various energy transport processes likely to be encountered in a hydrothermal-magma system, reviews related literature, discusses research and field data needs, and reviews the sites from an energy transport viewpoint. At least three major zones exist in the magma-hydrothermal transport system: the magma zone, the hydrothermal zone, and the transition zone between the two. Major energy transport questions relate to the nature and existence of these zones and their evolution with time. Additional energy transport questions are concerned with the possible existence of critical state and super-critical state permeable convection in deep geothermal systems. A review of thermal transport models emphasizes the fact that present transport models and computational techniques far outweigh the scarcity and quality of deep field data. This points out the need for a Continental Scientific Drilling Program which can begin to generate field data from deep holes. Interpretation of future field data, however, will require the use of many of the models that the data are designed to verify.

CONTINENTAL SCIENTIFIC DRILLING: COMPARATIVE ASSESSMENT OF FIVE POTENTIAL SITES FOR HYDROTHERMAL-MAGMA SYSTEMS, SAND80-1953A, H. C. Hardee, W. C. Luth, Sandia National Laboratories EOS Vol. 61, No. 46, November 11, p. 1148, Proceedings of American Geophysical Union, San Francisco, California, December 8-12, 1980.

A comparative assessment of five potential hydrothermal-magma sites for the Continental Scientific Drilling Program (CSDP) has been prepared for the DOE Office of Basic Energy Sciences. Four DOE laboratories (Los Alamos National Scientific Laboratory, Lawrence Berkeley Laboratory, Lawrence Livermore Laboratory, and Sandia National Laboratories (participated in this study. The five sites are: The Geysers-Clear Lake, California; Long Valley, California; Rio Grande Rift, New Mexico; Roosevelt Hot Springs, Utah; and Salton Trough, California. The need for a comparative site assessment study for Continental Scientific Drilling is an outgrowth of the Workshop on CSDP held at Los Alamos in 1978 which identified Thermal Regimes as one of the major objectives of Continental Scientific Drilling. Development of a fundamental understanding of energy transport within and between hydrothermal and magma systems is the obvious objective of the Thermal Regimes portion of CSDP. This site assessment study has gathered together background information (geology, geochemistry, geophysics, and energy transport) on the five sites. Natural criteria for site selection are that potential have identifiable, or likely hydrothermal systems and associated magma sources and that important scientific questions can be identified and answered by deep scientific holes at such sites.

THE GEOLOGY OF MAGMA SYSTEMS BACKGROUND AND REVIEW, SAND80-1959, Alan R. Peterfreund, Sandia National Laboratories, November 1980.

A review of basic concepts and current models of igneous geology is presented. This review is intended for the non-geologists involved in

magma energy studies. Emphasis is centered on studies of magma generation, ascent, emplacement, evolution, and surface or near-surface activity. An indexed reference list is also provided to facilitate future investigations.

SOLIDIFICATION IN KILAUEA IKI LAVA LAKE, Harry C. Hardee, Sandia National Laboratories, Journal of Volcanology and Geothermal Research 7 (1980) 211-223.

The crust of Kilauea Iki lava lake currently consists of an upper porous two-phase (water/steam) convection zone 41 m thick and a lower conduction zone 12 m thick extending to the melt. Although the solidification of the crust initially followed the classical square root of time law, the crust has been solidifying at a constant rate of 6.7 x 10^{-8} m/s for the past twelve years. The thickness of the lower zone of the crust also appears to have reached a constant value of 12 m. A moving solidification front solution is developed which shows that the constant solidification rate and constant thickness of the lower crust zone are natural outcomes of a heat balance between the two zones of the crust. Observed temperature profile curvature from borehole temperature measurements in the lake can be explained in terms of the solidification front solution. The solution and temperature profile data can be used to estimate an average in-situ permeability of 0.30 darcy for the upper zone of the crust which agrees well with measured values.

B. Source Tapping

DRILLING INTO MOLTEN ROCK AT KILAUEA IKI, John L. Colp, Sandia National Laboratories, Reginald T. Okamura, USGS, Transactions, Geothermal Resources Council, Vol. 2, July 1978, Hilo, Hawaii.

The Sandia Magma Energy Research Project is assessing the scientific feasibility of extracting energy directly from buried circulating magma resources. One of the tasks of the project is the study of geophysical measuring systems to locate and define buried molten rock bodies. To verify the results of a molten rock sensing experiment performed at Kilauea Iki lava lake, it is necessary to drill a series of holes through the solid upper crust and through the molten zone at that location. Thirteen holes have been drilled in Kilauea Iki; eleven by other groups and two by Sandia. The results achieved during the drilling of the two Sandia holes have indicated that the molten zone in Kilauea Iki is not a simple, relatively homogeneous fluid body as expected. The encountering of an unexpected, unknown rigid obstruction 2.5 ft below the crust/melt interface has led to the conceptual development of a drilling system intended to have the capability to drill through a hot, rigid obstruction while the drill stem is immersed in molten rock. The concept will be field tested in Kilauea Iki in the summer of 1978.

BOREHOLE STABILITY IN IGNEOUS ROCKS AT LOW PRESSURES AND TEMPERATURES TO PARTIAL MELTING, M. Friedman, J. Handin, N. G. Hibbs, and J. R. Lantz, Center for Tectonophysics, Texas A&M University, under contract to Sandia National Laboratories, Proceedings of Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16-22, 1979.

Energy extraction from magma requires stable boreholes at relatively shallow depths (< 10 km) in rocks at temperatures of the order of 1000°C. Accordingly, the failure strengths, permanent strains, and associated deformation mechanisms of room-dry andesite, basalt, granodiorite, and obsidian are determined at temperatures to partial melting (> 1050°C), at confining pressures of 0 and 50 MPa, and a strain rate of 10^{-4}/s. The strength reductions of the crystalline rocks are more or less linear until they steepen suddenly with approach to melting. When that occurs, strengths vanish and deformations become quasiviscous with equivalent viscosities of the order of 10^{7} to 10^{9} N · s/m^2. The obsidian is stronger than the crystalling rocks to 600°C where glass softening begins and strength goes to zero at 800°C ($\eta = 10^{10}$ N · s/m^2. All rocks are brittle throughout the entire temperature range until melting or softening occurs. Shortenings at failure are 2 percent or less unconfined, and 6 percent at most, at 50 MPa.

WATER JET DRILLING IN LIQUID LAVA, J. C. Dunn and P. C. Montoya, Sandia National Laboratories, Proceedings of Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16-22, 1979.

Two new concepts for entering and drilling into molten rock under local fluid pressure were tested in the Kilauea Iki lava lake during January, 1979. Previous attempts to drill with conventional techniques in liquid lava at Kilauea Iki failed, primarily for two reasons. First, standard water pressure is below local formation pressure of the lava.

When melt was encountered, lava entered the bit and solidified, sealing off all water passages before the water pump could respond to a sudden blockage. Secondly, since the drill hole is nominally at one atmosphere pressure, liquid lava was forced up the drill hole a considerable distance, freezing the drill rod in place. The new drilling equipment and procedures were designed to solidify liquid lava ahead of the bit by a forward jetting of water with nozzle stagnation pressure always greater than local formation pressure. One technique used a standard 3-wing drag bit modified by the addition of a central nozzle which produced a high velocity jet. The second concept employed a standard face-discharge diamond core bit modified by the addition of nozzle inserts in each of the discharge ports to produce six high velocity jets.

STRENGTH AND DUCTILITY OF ROOM-DRY AND WATER-SATURATED IGNEOUS ROCKS AT LOW PRESSURES AND TEMPERATURES TO PARTIAL MELTING, SAND80-7159, M. Friedman, J. Handin, N. G. Higgs, J. R. Lantz, and S. J. Bauer, Center for Tectonophysics, Texas A&M University, under Contract No. 13-2242 with Sandia National Laboratories.

Energy extraction from magma requires stable boreholes at relatively shallow depths (< 10 km) in rocks at temperatures approaching partial melting. Accordingly, the failure strengths, strains at failure, and associated deformation mechanisms are determined at temperatures to partial melting (> 1050°C) and a strain rate of $10^{-4}s^{-1}$ for, a) room-dry Mt. Hood Andesite, Cuerbio Basalt, and Charcoal Granodiorite at confining pressures of 0, 50, and 100 MPa, b) H_2O saturated specimens of these same crystalline rocks at zero effective confining pressure (pore and confining pressures of 50 MPa), and c) room-dry Newberry Rhyolite Obsidian at 0 and 50-MPa confining pressure. The strengths of the dry crystalline rocks are a nearly linear function of mean stress, and they decrease nearly linearly with increasing temperatures from 25°C to 800-900°C. At higher temperatures the strengths decrease rapidly and vanish upon partial melting when the deformation become quasiviscous. The obsidian is stronger than the crystalline rocks at 600°C where glass softening begins and its strength goes to zero at about 800°C. Water-weakening is evident only in the andesite. Its strength degrades dramatically between 850 and 880°C, at which temperature its ultimate strength is between 5 and 25 MPa compared to an average dry strength of 75 MPa at 1000°C. All rocks are brittle throughout the entire temperature range until melting or softening occurs. Shortenings at failure (ultimate strengths) are 3 percent or less in dry tests and $\leq$ 1 percent in most wet ones.

C. Magma Characterization

EXPERIMENT PLAN FOR CHARACTERIZATION OF THE PROPERTIES OF MOLTEN ROCK AT ATMOSPHERIC AND ELEVATED PRESSURES: MAGMA ENERGY RESEARCH PROJECT, SAND78-2227, P. J. Modreski, Sandia National Laboratories.

Knowledge of the properties of molten rock (magma) is of importance to the Magma Energy Research Project of Sandia National Laboratories. Facilities have been set up at Sandia to study the physical properties, chemistry, and corrosive nature of magma to 1600°C from atmospheric pressure to 4 kbar (400 MPa). Experiments at atmospheric pressure are being done in the presence of multicomponent gas mixtures to control the chemical activities of oxygen and sulfur. The high-pressure apparatus includes cold-seal small-volume pressure vessels (to 1100°C and 1 kbar). The large vessel contains a number of penetrations for electrical leads and pressure lines, and is linked to a computer for data acquisition and control of experiments. Water and other dissolved volatiles (CO_2, CO, SO_2, S_2, H_2S, HCL, HF) have significant effects on all the properties of magma, and these effects will be studied in the high-pressure apparatus. Phase equilibria, viscosity, electrical conductivity, and materials compatibility will be the first properties to be examined under pressure. This report includes a review of the nature and chemical basis for the effects of dissolved volatiles on these properties of magma.

EVALUATION AND RESTORATION OF THE 1970 VOLCANIC GAS ANALYSES FROM MOUNT ETNA, SICILY, T. M. Gerlach, Sandia National Laboratories, Journal of Volcanology and Geothermal Research 6 (1979) 165-178.

The 1970 Mount Etna volcanic gas analyses (Huntingdon, 1973) are among the most reduced volcanic gas samples ever reported. They contain 20-40% H_2, 2-3.5% CO, and 2-5% H_2S. Calculated oxygen fugacities for most of the analyses are well below quartz-fayalite-magnetite, several are more measured by Sato and Moore (1973) in the gas-streams of the collection sites at the time the samples were taken. The analyses show no similarity to calculated equilibrium compositions at any temperature. Deviations between analytical and equilibrium compositions indicate the gases have undergone extensive reduction involving mainly loss of oxygen. There also is limited evidence of sulfur loss. The reduced analyses are not the products of unusually reduced lavas, but originated from reactions of the erupted gases with the metal sampling device used in the collection procedure. The oxygen deficiencies of the analyses have been restored using the atomic hydrogen, carbon and sulfur data of Huntingdon and the oxygen fugacity data of Sato and Moore. The restored analyses are much more representative of the erupted gases which were remarkably rich in CO_2 (15-35%) and SO_2 (15-35%), and they show relatively steady compositions at each collection site over periods of observation ranging from hours to days.

COMPOSITIONS OF GASES COLLECTED DURING THE 1977 EAST RIFT ERUPTION, KILAUEA, HAWAII, E. J. Graeber, P. J. Modreski and T. M. Gerlach, Sandia National Laboratories, Journal of Volcanology and Geothermal Research, 5 (1979) 337-344.

Several high-temperature (950-1060°C) gas samples were collected with a new sampling device from lava flows and a vent during the September 1977 Kilauea eruption. After removal of atmospheric contaminants

(N_2, Ar, O_2), the gases are water-rich (90-95 mole %). This may be attributed to meteoric water or be indicative of relatively degassed, partially cooled magma that filled the rift zone. Numerous hydrocarbons in addition to CH_4 were present in a sample obtained in the presence of pyrolyzing vegetation.

MEASUREMENT OF IN-SITU PERMEABILITY IN KILAUEA IKI LAVA LAKE, HAWAII, SAND79-0349, J. C. Dunn and H. C. Hardee, Sandia National Laboratories, Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16-22, 1979.

The apparent permeability of solidified lava in the upper crust of Kilauea Iki lava lake was measured at several depths during December, 1978. The drill hole used (designated 79-1) was located near the center of the lake. Permeability was determined by injecting water into the formation at a constant flow rate while measuring downhole pressure rise as a function of time. A balloon packer was used to isolate the region of water injection. Measurements were taken at three depths -- 15.2, 34.7 and 39.0 meters. Inspection of the 79-1 core for regions of fracture indicated the following: 1) solid rock with no fracturing in the vicinity of 15.2 meters, 2) a fracture zone running directly through the region of water injection at 34.7 meters, and 3) a fracture present approximately 1 meter above the region of water injection at 39.0 meters.

Preliminary analysis of the water injection data indicates an apparent permeability of approximately 0.12 Darcy at 15.2 meters and a somewhat lower value of 0.09 Darcy at 39.0 meters. Near the fractured zone at 34.7 meters, apparent permeability was initially about 0.3 Darcy. Additional fracturing by the injected water then increased permeability to approximately 0.8 Darcy.

VOLCANIC GASES FROM ERTA ALE VOLCANO AND SURTSEY VOLCANO AND MAGMA OUTGASSING IN CRUSTAL SPREADING ZONES, T. M. Gerlach, Sandia National Laboratories, Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16-22, 1979.

The analyses of 82 volcanic gas samples collected in 1971, 1973 and 1974 from Erta Ale lava lake (Tazieff, et al., 1972; LeGuern, et al., 1975; Giggenbach and LeGuern, 1976) display moderately to intensely erratic compositions resulting from modifications imposed during and after collection. Sets of restored analyses obtained by systematic removal of the modifications are H_2O rich (70-80%), have O_2 fugacities near quartz-magnetite-fayalite (QMF), and show almost no evidence of short-term (minute-hours) chemical fluctuations. The 1971 and 1973 gases have similar compositions, but there is a decrease in CO_2 and an increase in H_2O between 1973 and 1974 which is qualitatively compatible with lava degassing controlled largely by solubility differences for CO_2 and H_2O in silicate melts.

A study of volcanic gas collections from Surtsey volcano eruptions between 1964 and 1967 (Sigvaldason and Elisson, 1968) gave similar results after removal of small modifications imposed during collection. The restored compositions also have O_2 fugacities near QMF and show a long-term decrease in CO_2.

VOLCANIC GASES AND COMPATIBILITY WITH PURE METALS, T. M. Gerlach, Sandia National Laboratories, Proceedings, Hawaii Symposium on Intra-plate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 1979.

Materials incompatibility is a potential problem confronting schemes for energy extraction from magma bodies. Chemical incompatibility between magmatic volatiles and metals is of particular concern. The purpose of this study is to describe the chemical characteristics of magmatic gases, inferred from existing volcanic gas collections, as a prelude to assessing metal incompatibilities.

Existing "high quality" volcanic gas samples are restricted to approximately 100 high temperature (> 950°C) collections obtained in source regions of tholeiitic and alkaline mafic lavas. These samples have erratic compositions which compromise attempts to characterize the chemistry of magmatic gases. Detailed studies of the analyses have identified several modifications, in addition to atmospheric contamination, which have been imposed on the samples during or after collection.

THE CALCULATION AND USE OF CVD PHASE DIAGRAMS WITH APPLICATIONS TO THE Ti-B-Cl-H SYSTEM 1200K-800K, E. Randich and T. M. Gerlach, Sandia National Laboratories, SAND80-0308.

A simple method for calculating multi-component gas-solid equilibrium phase diagrams for chemical vapor deposition (CVD) systems is presented. The method proceeds in three steps: determination of stable solid assemblages, evaluation of gas-solid stability relations, and calculation of conventional phase diagrams using a free energy minimization technique. The phase diagrams can be used to determine 1) bulk compositions and phase fields accessible by CVD techniques, 2) expected condensed phases for various starting gas mixtures, and 3) maximum equilibrium yields for specific CVD process variables. The three step thermodynamic method is used to calculate phase diagrams for the example CVD system Ti-B-Cl-H at 1200K and 800K. Examples of applications of the diagrams for yield optimization and experimental accessibility studies are presented and discussed. Experimental verification of phase field boundaries at 1200K, H/Cl = 1 and H/Cl = 5 confirms the calculated boundaries and indicates that equilibrium is nearly and rapidly approached in this system under laboratory conditions.

DEVELOPMENT OF HIGH TEMPERATURE VISCOSITY MEASUREMENT TECHNIQUE, SAND80-0641, Sandia National Laboratories, R. P. Wemple, W. F. Hommetter, and C. J. Greenholt, April 1980.

Viscosity measurements with magmatic rock at high temperatures and occasionally at elevated pressures are nontrivial problems. This report details the conception, development, and testing of : 1) an electromagnetic viscometer, and 2) an x-ray technique. Both methods employ a falling metallic sphere in the melt and provide real-time data.

Initial testing of the electromagnetic viscometer was performed at one bar and from 700-1300°C. Follow-on experiments with this viscometer were carried out at 1 bar and 0.466 kbar (6.8 kpsi) aron up to 1250°C at the Sandia Magma Energy Research Test Facility. The x-ray method was tested entirely at one bar and up to 1325°C. A simultaneous test series with both methods was performed at one bar.

EVALUATION OF VOLCANIC GAS ANALYSES FROM SURTSEY VOLCANO, ICELAND, 1964-1967, T. M. Gerlach, Sandia National Laboratories, Journal of Volcanology and Geothermal Research, 8 (1980) 191-198.

Methods developed in previous studies have been used to evaluate volcanic gas collections from eruptions of Surtsey between 1964 and 1967. The reported analyses for eight high-temperature (1125°C) samples taken at or very near the crater closely approach a state of chemical equilibrium. They have been only slightly affected by atmosphere contamination and by reduction processes resulting from interactions with stainless steel collection tubes. After corrections for these alterations, all resulting compositions are relatively water-rich; they contain 80-90% H_2O, 1-10% CO_2, 2-4% SO_2, 1.5-3% H_2, 0.1-0.7% CO, 0.1-0.9% H_2S and 0.01-0.25% S_2. O_2 fugacities are approximately on the quartz-magnetite-fayalite buffer at the collection temperature. The water-rich gas compositions are consistent with the observed degassing patterns of submarine basalts from progressively shallower depths along the Reykjanes Ridges.

INTERPRETATION OF VOLCANIC GAS DATA FROM THOLEIITIC AND ALKALINE MAFIC LAVAS, T. M. Gerlach, Proceedings of PIRPSEU Workshop on Volcanic Gases, CNRS, Gip-sur-Yvette, France, July 3-4, 1980.

The chemistry of magmatic volatiles is of significance to several fundamental geochemical questions, including aspects of the origin of magmas, ore deposits, and the atmosphere, hydrosphere, and biosphere. In recent years, environmental problems and the need for an eruption prediction and monitoring technology have also contributed to an interest in the chemistry of magmatic gases.

The extreme range of compositions displayed by volcanic gas analyses has complicated attempts to apply volcanic gas data to the above problems. This obstacle persists even in analyses of gases collected at high temperatures in the source regions of actively degassing lavas. The variability is partly from chemical alterations imposed on samples during collection, which are often related to the trying circumstances under which the collections are obtained.

EVALUATION OF VOLCANIC GAS ANALYSES FROM KILAUEA VOLCANO, T. M. Gerlach, Sandia National Laboratories, J. Volc. and Geoth. Res., V. 7, 295-317, 1980.

Much of the chemical variation and disequilibrium in Kilauean volcanic gas analyses is the result of contamination by meteoric water and, to a lesser extent, organic matter. Contamination by meteoric water is extensive in some samples, causing variations of two to three orders of magnitude in atomic H/C. Several of the widely quoted analyses for Jaggar's J-series collection are severely contaminated with meteoric water that did not equilibrate with the "magmatic" gases and consequently gives the analyses a disequilibrium appearance. When the contaminating H_2O is removed, the analyses converge to equilibrium mixtures in the temperature range 1085°C to 1185°C with O_2 fugacities slightly above those for the quartz-magnetite-fayalite buffer. The restored analyses are richer in CO_2 (18-50%) and SO_2 (10-21%) and poorer in H_2O (37-70%) than are the original analyses.

INVESTIGATION OF VOLCANIC GAS ANALYSIS AND MAGMA OUTGASSING FROM ERTA ALE LAVA LAKE, AFAR, ETHIOPIA, T. M. Gerlach, Sandia National Laboratories, J. Volc. and Geoth. Res., V. 7, 415-441, 1980.

The analyses of 18 volcanic gas samples collected over a two-hour period at 1075°C from Erta Ale lava lake in December 1971 and of 18 samples taken over a half-hour period at 1125°C to 1135°C in 1974 display moderately to intensely variable compositions. These variations result from imposed modifications caused by 1) atmospheric contamination and oxidation, 2) condensation and re-evaporation of water during collection, 3) analytical errors, and 4) chemical reactions between the erupted gases and a steel lead-in tube.

COMPOSITIONS AND PROPORTIONS OF MAJOR PHASES IN THE 1959 KILAUEA IKI LAVA LAKE IN DECEMBER 1978, W. C. Luth and T. M. Gerlach, Sandia National Laboratories, EOS Transactions, American Geophysical Union, Volume 61, Number 46, November 11, 1980, 1980 AGU Fall Meeting.

Twelve element quantitative electron microprobe analyses on phases in 30 samples of 3 drill holes penetrating magma were used to define 4 zones in the lava lake. Depths to zones vary due to a biconvex magma zone. At 285 m north of the center the zones are: Upper Curst (UC), 0-50.5 m; Upper Magmatic Transition Zone (UMTZ), 50.5-53.5 m; Magma Zone (MZ), 53.5-61 m; Lower Magmatic Transition Zone (LMTZ), 61-63(?) m. The lower crust was not penetrated in the drilling program. Glass compositions define smooth continuous paths on oxide variation and AFM diagrams, from basaltic in the LMTZ and MZ to rhyolitic in the UMTZ and UC. Glass compositions are constant in composition in the MZ and LMTZ although abundance decreases from 35% in the MZ to < 15% in the LMTZ. Glass abundance decreases in the UMTZ and UC (5%) accompanying the major compositive change. Olivine compositions are essentially constant (Fo (wt_{72}) in the MZ and LMTZ, with a range from Fo_{70-75} and no significant compositional difference between phenocrysts and microphenocrysts. Mean compositions become less Fo-rich and show greater dispersion about the mean in the UMTZ and UC. Olivine abundance varies over a wide (20-47%) range reflecting in situ crystallization crystal settling, and sub-solidus recrystallization. Plagioclase abundance is constant (15 vol %) in the MZ and LMTZ, increasing to 30-35 vol % in the UMTZ and UC. Mean plagioclase compositions decrease from An_{74} to An_{70} (wt) with decreasing depth in the LMTZ and MZ. Mean compositions become more sodic (An_{55}) and compositional dispersion increases in the UMTZ and UC. Clinopyroxene compositions are invariant with respect to composition in the LMTZ, MZ, UMTZ, and lower part of the upper crust.

MASS BALANCE DIFFERENTIATION MODELS FOR THE 1959 KILAUEA IKI LAVA LAKE, T. M. Gerlach and W. C. Luth, Sandia National Laboratories, EOS Transactions, American Geophysical Union, Volume 61, Number 46, November 11, 1980, 1980 AGU Fall Meeting.

Unweighted least squares mass balance differentiation models for Kilauea Iki lava lake have been calculated from published glass and lava compositions (S7, MURATA AND RICHTER, 1966) and new data for mineral, glass and bulk compositions of 11 samples (Chambers, et al., Luth, et al., this volume) from a recent drill hole penetrating a 11 m thickness of magma 285 m north of the lake center. The initial magma for the models was S7, which corresponds closely to the mean lava lake composition. Rocks of the Upper Magmatic Transition Zone (UMTZ, 50.5-53.5 m)

require addition of 15% (wt) olivine (ol, Fo_{80} (wt)) and 3-10% clinopyroxene (cpx, $Wo_{43}Em_{47}Fs_{10}$) relative to S7 but are less enriched than S5, the most picritic lava of the 1959 eruption. The Magma Zone (MZ, 53.5-61 m) is more enriched than S5, requiring addition of 20-35% ol (Fo_{80-75}), 5-10% cpx, and 3-10% plagioclase (pl, Am_{80}) down to 59 m. From 59 m to the Lower Magmatic Transition Zone (LMTZ, 61-63(?) m), rocks are consistent with enrichments > 100% ol, > 60% cpx, and > 25% pl. These results suggest the operation of accumulation mechanisms (crustal foundering, crystal settling, etc.) and indicate that wholerock compositions at depth do not follow simple olivine control lines, unlike the lavas erupted at lake formation. Models for the generation of glass (liquid) compositions in the UMTZ and MZ from an initial liquid, based on an analysis of glass is S7, require removal of 1-5% oxide, 13-15% ol, 25-35% cpx, 25% pl, and 10-15% alk feldspar in the UMTZ and removal of 10% ol, 15-25% cpx, and 15-20% pl in the MZ. The good fits (Σr^2 = .1-.3) and sensible results, in view of care exercised to avoid overfitting, reflect overall consistency of the data and support the choice of S7 starting compositions.

EVALUATION OF VOLCANIC GAS ANALYSIS FROM THOLEIITIC AND ALKALINE MAFIC LAVAS, T. M. Gerlach, Sandia National Laboratories, Proceedings of Workshop on Remote Sensing of Volcanic Gases; report available from Lunar and Planetary Institute, Houston, Texas 77058.

There are approximately 100 volcanic gas analyses of collections taken at high temperatures (> 950°C) in source regions of tholeiitic and alkaline mafic lavas (Hawaii, 1918-19; Nyiragongo, 1959; Surtsey, 1964-67; Etna, 1970; Erta Ale, 1971-74). These "high quality" volcanic gas samples exhibit erratic chemical characteristics. Atmospheric contamination has long been recognized as an obvious cause of much of the observed variability, however substantial compositional variation remains even after the analyses have been corrected for air contamination. This feature has compromised attempts by volcanologists to relate the collections in terms of temporal, spatial and petrologic parameters.

Detailed computerized studies of the "high quality" gas samples have led to an identification of several sources of modification in addition to atmospheric contamination. These include: addition of meteoric H_2O; condensation and re-evaporation of S and H_2O in lead-in tubes; reactions between the erupted gases and metal sampling equipment; oxidation of minor species (S_2, H_2S, H_2, CO); incomplete chemical analyses; and analytical errors in H_2O determinations. Reduced gases tend to result when samples are collected in metal sample bottles (e.g., Etna, 1970). Samples taken with evacuated glass tubes have frequently become oxidized (e.g., Erta Ale, 1971). The least modified samples are those taken in glass sample bottles connected to metal lead-in tubes (Surtsey, 1964-67 and Erta Ale, 1974). Most techniques have provided little or no direct information on HCl, HF, H_2S, S_2 and COS. The author has developed procedures for correcting the reported analyses for several of the imposed modifications noted above.

D. Energy Extraction

EXTRACTION OF HEAT FROM MAGMAS BASED ON HEAT TRANSFER MECHANISMS, H. C. Hardee, D. W. Larson, Sandia National Laboratories, J. Volcanol. Geotherm. Res., V. 2, No. 2, pp. 113-144, July 1977.

Analytical heat transfer calculations are used to relate geological surface evidence to conditions that should exist in magma chambers for the purpose of improving estimates of possible commercial heat extraction rates. These calculations indicate that an upward-melting magma system necessarily is approximately equidimensional and that injected magmas with very high aspect (L/D) ratios are likely formed by a forced intrusion process which involves little if any melting or natural convection. Calculations along with surface heat flow measurements suggest that steady-state heat extraction rates for emplaced heat exchangers in currently suspected shallow magma chambers will probably be below 10 kW M_{-2}, a value that is low by engineering standards.

THE EXTRACTION OF HEAT FROM MAGMA BODIES, H. C. Hardee, Jr., Sandia National Laboratories, A. Herschman, Editor, Am. Assoc. Adv. Sci., Washington, DC, p. 111, 1978, Proceedings of AAAS 144th National Meeting, Washington, DC, February 12-17, 1978.

Analytical heat transfer techniques are used to relate geological surface evidence and observations to conditions that are likely to exist in magma chambers. An experimental heat exchanger was tested in a molten lava source heated by an induction furnace. Design work has been started on a prototype long tube heat exchanger. This information is being used to make estimates for commercial heat extraction rates. Calculations and surface heat flow measurements indicate that the steady-state heat extraction rates for shallow convecting magma chambers with low superheat will probably be on the order of 10 kw/m^2 or less and a lower limit of around 1 kw/m^2 will occur for conduction dominant magma chambers. Preliminary cost comparisons indicate that magma power would be competitive with conventional power plants at magma heat extraction rates of 4 kw/m^2 or more.

HEAT-TRANSFER MEASUREMENTS IN 1977 KILAUEA LAVA FLOW, H. C. Hardee, Sandia National Laboratories, Transactions, American Geophysical Union, Vol. 59, No. 4, p. 311, 1978.

The 1977 Kilauea eruption (September-October 1977) produced a river of basaltic lava which flowed for several days. During this eruption an experiment was performed in which a heat transfer probe, containing two heat flux gauges, was inserted into the lava river about 50 meters from the Puu Kiai vent. Five minutes of data were obtained during the test and heat fluxes were recorded ranging from 200 kW/m^2 down to 10 kW/m^2. The measurements correlated well with theoretical calculations of heat flux based on the best current knowledge of lava properties. Analysis of the data indicated that vesicles and interface contact gaps were likely present in the lava crust that solidified on the surface of the heat flux gauges. There was also an indication that one of these heat flux gauges may have been approaching a convective heat transfer limit around 5 kW/m^2 near the end of the test. A test with a second thermal probe indicated that the lava had an effective thermal diffusivity of 1.88×10^{-3} cm^2/s in the temperature range of 900-1100°C. This value of diffusivity is consistent with currently known lava properties

when either vesicle or phase change effects are included. The information gained from these tests will be very useful in the design of future heat transfer probes and heat exchangers for use in lava or magma.

MAGMA: A POTENTIAL SOURCE OF FUELS, C. J. M. Northrup, Jr., T. M. Gerlach, P. J. Modreski and J. K. Galt, Sandia National Laboratories, International Journal of Hydrogen Energy, Vol. 3, pp. 1-10, 1978.

Recent calculations and measurements indicate that basaltic magma is a new, extensive source for fuels (hydrogen, carbon monoxide, and methane). The fuel production processes have been found to occur in nature as well as the laboratory and as a result, our work indicates that current concepts of geothermal energy can be broadened beyond producing only steam and heat. When magma is considered as a geothermal resource, its use for the direct production of fuels should be included. It is possible to generate several mole percent hydrogen when water-rich fluid is equilibrated with the ferrous and ferric iron in magma. This paper describes the basis of the fuel production processes, the fuel yields for injected water and water plus natural organic matter (biomass), and the increased geothermal resources that would be made available by these processes.

HEAT TRANSFER MEASUREMENTS IN THE 1977 KILAUEA LAVA FLOW, HAWAII, H. C. Hardee, Journal of Geophysical Research, Vol. 84, No. B13, December 10, 1979, pp 7485-7493.

The September-October 1977 eruption of Kilauea volcano, Hawaii, produced a river of basaltic lava which flowed for several days. A heat transfer probe containing two heat flux gauges measured the conduction-dominant heat transfer rates from molten lava into a cold probe inserted in an eddy in the lava river. During a five-minute test period the primary heat flux gauge indicated transient-decaying conduction-dominant heat fluxes ranging from 200 kW/m^2 down to 50 kW/m^2. A secondary heat flux gauge verified that convective heat flux rates, due to either natural or forced convection in the eddy, were of the order of 10 kW/m^2 or less. Theoretical calculations of the expected conduction-dominant heat transfer rates between the lava and the probe agree with the experimental data from the primary gauge to within an error of 20% or less. The type of information gained from this field experiment is useful in predicting such diverse things as potential energy extraction rates for heat exchangers in lava or magma as well as the thickness of the solid wall of the natural levee containing a lava flow. Future heat transfer experiments should investigate the low convection heat flux range (below 10 kW/m^2) in eddys and the much higher forced-convection heat flux range in the main channel of lava rivers.

HEAT EXTRACTION FROM MAGMA BODIES, SAND79-0254A, H. C. Hardee, Sandia National Laboratories, Proceedings of Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16-22, 1979.

Heat extraction rates for closed heat exchanger systems in basaltic magma range from 1 to 10 kw/m^2 depending on the degree of convection in the magma adjacent to the heat exchanger surface. For silicic

magmas, the heat extraction rate is limited by conduction to about 1 kw/m^2 for reasonable plant-life assumptions. An economic break-even point for closed heat exchanger systems occurs at heat transfer rates around 5 kw/m^2. It therefore appears that only the better basaltic magmas might prove economical for heat extraction with closed heat exchanger systems.

Various open heat exchanger systems could improve the effective heat extraction rate by one and possibly two orders of magnitude. The open heat exchanger systems are usually based in principle on some means of increasing the effective surface area of the exchanger. One method is to form a large porous crust around the exchanger and pass a heat transfer fluid through this porous region. The "huff and puff" concept is one such example where the heat transfer fluid is alternately injected and removed from the porous region. This concept is somewhat similar to a technique used in tertiary oil recovery where a working fluid is pumped into a porous cavity and heated oil is removed periodically.

E. Field Experiments

FY-79 LAVA LAKE DRILLING PROGRAM: RESULTS OF DRILLING EXPERIMENTS, SAND79-1360, R. R. Neel, R. P. Striker, R. M. Curlee, Sandia National Laboratories, December 1979.

A drilling program was conducted in December 1978 and January and February 1979 to continue the characterization of the solid and liquid rock components of the Kilauea Iki lava lake. Six holes were drilled from the surface and two previously drilled holes were reentered and deepened for the purposes of measuring downhole temperature profiles, recovering samples of solid, plastic, and molten rock, measuring crust permeability, and determining the performance of conventional and special drilling techniques. Conventional HQ-size (3.78 inches diameter) core drilling equipment using water for cooling and cuttings removal was used to successfully drill during initial entry into 1052°C formations. Conventional drilling in reentering flow-back rock was less reliable. The specially designed water jet-augmented drag bit or water jet-augmented core bit was needed to drill reliably into the plastic flow-back rock and through liquid rock veins. This document contains the drill performance data which were recorded during drilling in the crust and the plastic and molten rock zones using both conventional and special drilling procedures and equipment.

FY-79 LAVA LAKE DRILLING PROGRAM -- GEOSCIENCE STUDIES: PLANS AND RESULTS, SAND79-1361, John L. Colp, Sandia National Laboratories, October 1979.

Fifteen experimental studies were planned for the geoscience studies portion of the FY-79 lava lake drilling program at Kilauea Iki lava lake, Hawaii, grouped under headings of petrologic, thermal, strength, liquid/permeability, electrical, and other. This report gives a location, purpose, description and feasibility analysis for each experiment. A results section for each experiment includes data gathered and analysis to date, where available.

KILAUEA IKI LAVA LAKE EXPERIMENT PLANS, SAND80-1653, J. C. Dunn and R. G. Hills, Sandia National Laboratories, January 1981.

Twelve experimental studies are proposed to complete Sandia's field laboratory work at Kilauea Iki lava lake. Of these twelve experiments, eleven do not require the presence of melt. Some studies are designed to use proven techniques in order to expand our existing knowledge, while others are designed to test new concepts. Experiments are grouped into three main categories: geophysics, energy extraction, and drilling technology. Each experiment is described in terms of its location, purpose, background, configuration, operation, and feasibility.

F. Miscellaneous

VISCOUS DISSIPATION EFFECTS IN MAGMA CONDUITS, H. C. Hardee, D. W. Larson, Sandia National Laboratories, Journal of Volcanology and Geological Research, Vol. 2, No. 3, pp 299-308 (1977).

Fujii and Yueda (1974) postulated that viscous dissipation may lead to thermal instability and explosive eruptions in the case of volcanic conduits or dikes. Although their conclusions were based on a viscosity function which was valid over a very narrow temperature range, calculations presented here lead to the same result for critical dike width. A simple forced intrusion model, without viscous dissipation effects, is also developed and found to be sufficient to explain the observed width of volcanic conduits and dikes. The mechanism of thermal runaway may present problems for magma energy extraction.

REPORT OF THE WORKSHOP ON MAGMA/HYDROTHERMAL DRILLING AND INSTRUMENTATION, SAND78-1365C, S. G. Varnado and J. L. Colp, Sandia National Laboratories, July 1978.

This report summarizes the discussions, conclusions, and recommendations of the Magma/Hydrothermal Drilling and Instrumentation Workshop which was held in Albuquerque, New Mexico, May 31-June 2, 1978. The purpose of the workshop was to define potential drilling environments and to assess the present state-of-the-art in drilling and instrumentation technology for a drill hole that would penetrate through deep hydrothermal systems and into a magma body. This effort is envisioned as a portion of a larger program of continental drilling for scientific purposes which has been proposed by the U. S. Geodynamics Committee of the National Academy of Sciences. For the purposes of the workshop, three working groups were organized as follows: Drilling Location and Environment, Drilling and Completion Technology, and Logging and Instrumentation Technology.

THE CORROSION OF SOME PURE METALS IN BASALTIC LAVA AT 1150°C, SAND79-1981, D. L. Douglass, P. J. Modreski, and J. T. Healey, Sandia National Laboratories, Proceedings of Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 1979.

One method for the extraction of thermal energy from subterranean magma bodies involves the use of a suitable heat exchanger which would extend into the molten rock. Materials incompatibility may be one of the major potential problems. The objectives of this study were to determine basic compatibilities, to measure corrosion rates, and to determine the mechanism of the reaction and degradation. A number of pure metals have been exposed to molten Kilauea-1971, tholeiitic basalt at 1150°C for 24 to 96 hours. A cover gas was used to simulate the gas in solution in magma bodies, having a sulfur fugacity of 7.10×10^{-3} and an oxygen fugacity of 9.8×10^{-10}

PRELIMINARY ANALYSIS OF TWO ASPECTS OF MAGMA POWERED ELECTRIC GENERATION PLANTS, SAND80-1522, E. R. Hoover, Sandia National Laboratories, September 1980.

Two aspects critical to the development of magma electric generation plants using closed heat exchanger systems are addressed in this

study. The heat transfer between the cold fluid in the downcomer and the hot fluid in the upcomber is analyzed using an NTU-effectiveness technique. The results indicate the hot fluid must be thermally insulated from the colder fluid in order to yield a useful temperature difference at the surface. A preliminary system analysis is conducted to determine the well cost requirements of an economically competitive magma electric plant. There is no economic incentive to make the magma tap wellbore larger than conventional deep gas wells. The cost competitiveness of a magma/electric plant is influenced by the depth to the magma, the convective heat flux of the magma, and the expected life of each well.

G. Project Reviews/Summaries

MAGMA AS A GEOTHERMAL RESOURCE -- A SUMMARY, H. M. Stoller, J. L. Colp, Geothermal Resources Council, Transactions, Vol. 2, July 1978, p. 613.

The objective of the Magma Energy Research Project underway at Sandia Laboratories is to assess the scientific feasibility of extracting energy directly from deeply buried circulating magma sources. The USGS has estimated that the energy contained in molten and partially molten magma within 10 km of the surface within the U.S. at 5 x 10^4 quads. Methods of energy extraction under consideration include: the insertion of a heat exchanger into a magma source with surface conversion to electric power; and utilizing the reducing nature of magma to produce transportable fuels such as hydrogen and methane. Technical elements of the Magma Energy Research Project include: Source location and definition -- the development, demonstration and verification of exploratory techniques for locating and defining molten rock sources, Source tapping -- the assessment of the deep-rock, near-magma environment and the technology to drill into molten rock sources, Magma property and materials compatibility -- the definition of in situ properties of magma and the evaluation of engineering materials subjected to that environment, Energy extraction -- the examination and development of processes and systems capable of extracting energy from magma sources.

UTILIZATION OF MAGMA ENERGY, A PROJECT SUMMARY, J. L. Colp, H. M. Stoller, Sandia National Laboratories, AAPG Bulletin, American Association of Petroleum Geologists, Vol. 62, No. 7, p. 1212, 1978, also Proceedings, Second Circum-Pacific Energy and Mineral Resources Conference, July, 1978.

The scientific feasibility of extracting energy from magma bodies is the objective of this project. The high temperature (approximately 1000°C) and estimated large resource (approximately 10^4 quads) within 10 km of the surface in the U. S. provides the incentive for this work. The areal extent of a near-surface molten lava body has been defined with geophysical sensing systems. Improved knowledge of the in-situ physical properties of buried molten rock is required to assess the thickness of magma bodies. Drilling into molten lava is a complex operation and requires further technological development. Experimental studies of rock deformation at near-magma temperatures and pressures show that boreholes can be made to stay open. Calculational analyses of magmatic gas samples provide a satisfactory definition of the gas content of in-situ magmas. Material compatibility experiments show that ni- and co-based alloys can survive and operate in the magma environment. Thermal heat exchanges can survive in molten rock and allow significant rates of heat transfer to an internal fluid.

MAGMA ENERGY RESEARCH PROJECT -- STATUS REPORT AS OF OCTOBER 1, 1978, SAND78-2288, J. L. Colp and R. K. Traeger, Sandia National Laboratories, December 1979.

The Magma Energy Research Project is investigating the scientific feasibility of extracting energy from magma bodies. This report summarizes work done in FY-76, 77, and 78 in the four tasks of the project: 1) resource location and definition, 2) source tapping, 3) magma characterization and materials compatibility, and 4) energy extraction.

MAGMA ENERGY RESEARCH, 79-1, SEMIANNUAL REPORT, OCTOBER 1, 1978 - MARCH 31, 1979, SAND79-1344, R. K. Traeger, J. L. Colp, R. R. Neel, Sandia National Laboratories, July 1979.

A major effort in evaluating Kilauea Iki lava lake has been completed. The physical model based on FY-76 geophysical experiments is not correct in that a low viscosity, liquid lens of appreciable thickness does not exist. Mathematical models of the cooling of the lava lake and the state of solidification of the liquid lens were verified by thermal profile and permeability measurements. New jet-augmented drilling concepts successfully penetrated the viscous, multi-phase molten rock region in some locations where conventional drilling failed. Heat transfer studies in the lake suggest injection of fluids to enhance convection may be useful to extract energy from magma chamber margins. Other activities resulted in the completion and successful testing of an 800 cc simulation facility for evaluating simulated magma properties at temperatures to 1500°C and pressures to 4 kbar. In materials compatibility studies, thermodynamic stability diagrams were developed for 15 pure metals in basaltic magma systems and compatibility tests completed. Results are being used to define simple alloy systems which may be compatible with magmas and to identify other superalloy materials candidates.

MAGMA ENERGY RESEARCH PROJECT -- FY 1979 ANNUAL PROGRESS REPORT, SAND79-2205, John L. Colp, Sandia National Laboratories, December 1979.

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 1 is Resource Location and Definition, Task 2 is Source Tapping, Task 3 is Magma Characterization, Task 4 is Material Compatibility, and Task 5 is Energy Extraction.

MAGMA ENERGY -- A FEASIBLE ALTERNATIVE, SAND80-0309, J. L. Colp, Sandia National Laboratories, Proceedings of United National Institute for Training and Research Conference on Long Term Energy Resources, Montreal Canada, November 26-December 7, 1979.

This report provides a short review of the work performed by Sandia Laboratories in connection with its Magma Energy Research Project. Results to date suggest that boreholes will remain stable down to magma depths and engineering materials can survive the downhole environments. Energy extraction rates are encouraging. Geophysical sensing systems and interpretation methods require improvement, however, to clearly define a buried magma source.

MAGMA ENERGY RESEARCH PROJECT -- FY 1980 SEMI-ANNUAL PROGRESS REPORT, SAND80-2377, John L. Colp, 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 tasks representing all aspects of the concept. Results for the reporting period are presented for each task.

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