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Geothermal Technology Publications and Related Reports: A Bibliography, January Through December 1981

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Sandra R. Hudson, Editor

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
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GEOHERMAL TECHNOLOGY PUBLICATIONS AND RELATED REPORTS:

A BIBLIOGRAPHY

January through December 1981

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Abstract

Sandia National Laboratories has done significant research and development for the U. S. Department of Energy to understand and utilize geothermal resources. Results of the work from January 1977 through December 1980 as documented in the literature, were summarized in a previous report (SAND81-0662). This bibliography extends the past listing to work reported in the 1981 calendar year. Titles, authors and abstracts of papers are assembled into areas of Geothermal Technology, Magma and General Geoscience Studies with cross references listed by author.

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

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Several of the publications were made through the Geothermal Resources Council Transactions. The reference for those transactions is listed below:

GEOHERMAL ENERGY: THE INTERNATIONAL SUCCESS STORY,
Transactions, Volume 5, Geothermal Resources Council
Annual Meeting, October 25-29, 1981, Houston, Texas.

You may request the above transactions from the following address:

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

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

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

I. GEOTHERMAL TECHNOLOGY

Introduction

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

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

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

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

Well logging and downhole instrumentation R&D activities are organized under the diagnostics technology program element. The major thrust is in developing high-temperature electronic components, transducers and concomitant materials. A wellbore inertial navigator is also being developed.

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

A. Rock Penetration Mechanics

ANALYTICAL AND EXPERIMENTAL INVESTIGATIONS OF ROCK CUTTING USING POLYCRYSTALLINE DIAMOND COMPACT DRAG CUTTERS, SAND81-0497C, D. V. Swenson, D. L. Wesenberg, A. K. Jones, Sandia National Laboratories.

The design and optimization of polycrystalline diamond compact (PDC) bits requires an understanding of the mechanics of cutter/rock interaction. In this paper we describe analytical and experimental investigations of the rock cutting process using a single PDC drag cutter.

A material model for rock is presented in which fracturing can occur due to either tensile or shear stresses (Coulomb Criterion). The material model was used in finite element analyses of three prototypic tests conducted for model verification and then in analyses of drag cutting.

Corresponding single cutter/rock interaction experimental studies were conducted on Berea sandstone samples. The analytical cutter/rock interaction studies show good correlation with these experimental results, thus verifying that the finite element code can now be used for PDC bit design and optimization.

LABORATORY EVALUATION OF PDC DRILL BIT UNDER HIGH SPEED AND HIGH WEAR CONDITIONS, SAND81-0747, E. R. Hoover, Sandia National Laboratories, 56th Annual Technical Conference and Exhibition, Society of Petroleum Engineers, October 4-7, 1981, San Antonio, Texas.

The recent advances in high temperature turbodrill technology have generated a great deal of interest in the development of a drill bit capable of operating at the high speeds typically associated with these downhole motors. The high speed bit development program managed by Sandia National Laboratories for the Department of Energy has concentrated on polycrystalline diamond compact (PDC) drill bits because of their lack of moving parts and their successful use on turbines in the North Sea.

Recently six different PDC bit designs were tested in the laboratory under atmospheric conditions. Five of these bits were designed and built by the following commercial bit manufacturers: American Coldset, Christensen, NL Hycalog, Dresser/Security, and Smith. The sixth bit was developed at Sandia. In general, the designs were diverse and utilized different bit profiles, cutter placement strategies, and material selection rationales. This diversity allowed us to compare different design concepts.

The bits were tested in nugget sandstone, crab orchard sandstone, and Sierra White Granite at rotary speeds of both 100 and 500 RPM to establish their performance characteristics as a function of weight-on-bit. The dynamic response of each bit at 500 RPM was also evaluated. In addition, the wear of polycrystalline diamond compacts in the Sierra White Granite was characterized.

The primary objective of this paper is to present the experimental results and correlate the data with specific design options such as back rake angle and bit profile. For example, the -20° rake cutters are more aggressive in the sandstone than the -25° rake cutters. However, in the much tougher Sierra White Granite the -20° cutters experienced increased spalling in the diamond layer.

FAILURE MECHANISMS OF PDC DRILL BITS IN GEOTHERMAL ENVIRONMENTS, SAND81-1404, September 1981, Ed R. Hoover, Larry E. Pope, Sandia National Laboratories.

Over the past few years the interest in polycrystalline diamond compact (PDC) drill bits has grown proportionately with their successful use in drilling oil and gas wells in the North Sea and the United States. This keen interest led to a research program at Sandia to develop PDC drill bits suitable for the severe drilling conditions encountered in geothermal fields. Recently, three different PDC drill bits were tested using either air or mud drilling fluids: one in the laboratory with hot air, one in The Geysers field with air, and one in The Geysers field with mud. All three tests were unsuccessful due to failure of the braze joint used to attach the PDC drill blanks to the tungsten carbide studs. A post-mortem failure analysis of the defective cutters identified three major failure mechanisms: peripheral nonbonding caused by braze oxidation during the brazing step, nonbonding between PDC drill blanks and the braze due to contamination prior to brazing, and hot shortness. No evidence was found to suggest that the braze failures in The Geysers field tests were caused by frictional heating. In addition, inspection of the PDC-stud cutter assemblies using ultrasonic techniques was found to be ineffective for detecting the presence of hot shortness in the braze joint.

PHASE IV SEMI-ANNUAL REPORT -- PROGRAM FOR THE IMPROVEMENT OF DOWNHOLE DRILLING MOTOR BEARINGS AND SEALS, SAND80-7110, G. A. Tibbitts, et al., Terra Tek, Inc., under contract to Sandia National Laboratories.

This report summarizes the work performed for the first six-month period of Phase IV of the DOE/DGE Contract Number 07-7298, "Program for the Improvement of Downhole Drilling Motor Bearings and Seals." This reporting period saw four main areas of development for the project: 1) design and fabrication of a dynamometer and a mud cooling system for the Bearing-Seal Package Test Facility; 2) modification of the Bearing-Seal Package Test Facility based on test results; 3) testing of new lubricant samples from Pacer Lubricants, Inc., in the Terra Tek High Temperature Lubricant Tester; and 4) testing of new seal types in the Terra Tek Seal Tester.

DEVELOPMENT OF AN IMPROVED BEARING PACK FOR DOWNHOLE MOTORS IN GEOTHERMAL APPLICATIONS, Peter H. DeLaFosse, Alan D. Black, John L. Sandstrom and Gordon A. Tibbitts, Terra Tek, Inc., under contract to Sandia National Laboratories, Geothermal Resources Council, Transactions Vol. 5, October 1981.

A sealed bearing pack (called the Bearing-Seal Package) is being developed for use with downhole mud motors and turbines for geothermal applications. The Bearing-Seal Package contains a sealed lubrication system which allows the bearings to operate in oil instead of abrasive drilling mud. The key to the success of the lubrication system is the development of a reliable rotary seal that will operate under downhole conditions. The development program emphasizes extensive laboratory screening tests of candidate high temperature seals and lubricants. A Seal Test Machine has been constructed to test candidate high temperature seals under simulated downhole conditions. Descriptions of the Bearing-Seal Package and Seal Test Package and Seal Test Machine are presented. Candidate high temperature seals and lubricants are reviewed and seal tests are discussed.

PROGRAM FOR THE IMPROVEMENT OF DOWNHOLE DRILLING MOTOR BEARINGS AND SEALS, PHASE IV. FINAL REPORT, SAND81-7066, G. A. Tibbitts, P. H. DeLaFosse, A. Black, S. J. Green, Terra Tek, under contract to Sandia National Laboratories.

Test results are presented from the seal test machine and bearing-seal package. An overall program summary is given and the major milestones of this phase of the program are shown.

HIGH TEMPERATURE GEOTHERMAL ELASTOMER COMPOUND DEVELOPMENT,
Alan R. Hirasuna, L'Garde, Inc., under contract to Sandia
National Laboratories, Proceedings of the International
Conference on Geothermal Drilling and Completion Technology,
Albuquerque, New Mexico, January 21-23, 1981

Reliable casing packer seal elastomers for the unusually severe geothermal environment at 260°C (500°F) did not exist in 1976. L'Garde, Inc., was awarded a contract to fulfill this need by the U. S. Department of Energy. Successful development was completed in 1979. Compounds based on four different polymer systems were developed, all of which exceed the contract requirements. Successful laboratory tests above 300°C (575°F) have been performed with packer seals. Field tests to temperatures as high as 317°C (603°F) have been performed on static O-rings in a cablehead. Successful, dynamic, drill bit seal tests were run with a presoak temperature of 288°C (550°F). The successful compounds are based on the following polymer systems: EPDM (Nordel^R), FKM (Viton^R), EPDM/FKM (Nordel^R/Viton^R) blend, and propylene-TFE (AFLAS^R). Evaluation was performed on full-scale packer seals as well as on O-rings by L'Garde. L'Garde ran comparison tests against commercially available elastomers including Kalrez^R. Case histories of other organizations which have laboratory and/or downhole experience with one or more of the developed compounds are presented. The applications cited include blowout preventors, dynamic drill bit seals, packers, and cableheads. Finally, an effort to actively transfer this technology to the industry is described.

HIGH TEMPERATURE SEALS AND LUBRICANTS FOR GEOTHERMAL ROCK BITS:
FINAL REPORT, SAND81-7076, R. R. Hendrickson, Terra Tek, Inc.,
under contract to Sandia National Laboratories.

High temperature seals (elastomeric and mechanical) and lubricants were developed specifically for journal-type rock bits to be used in geothermal well drilling. Results at simulated downhole conditions indicate that five selected elastomeric seals (L'Garde No. 267, Utex Nos. 227, 231 and HTCR, and Sandia Glow Discharge Coated Viton) are capable of 288°C (500°F) service. Two prototype mechanical seals did not achieve the life determined for the elastomeric seals. Six lubricants (Pacer PLX-024 oil, PLX-043 oil, PLX-045 oil, Geobond Oil, and Geobond Grease) demonstrated 316°C (600°F) capability. Recommendation is made for full-scale simulated geothermal drilling tests utilizing the improved elastomeric seals and lubricants.

INVESTIGATION OF PERCUSSION DRILLS FOR GEOTHERMAL APPLICATIONS, SAND81-0443C, John T. Finger, Sandia National Laboratories, Proceedings of 56th Annual Technical Conference and Exhibition, Society of Petroleum Engineers, October 4-7, 1981, San Antonio, Texas, SPE Paper 10238.

Several downhole percussion drills were run in uniform rock samples to compare their performance over a range of bit weights and flow conditions. Percussion drills with roller bits gave rates of penetration 2-1/2 to 3 times that of the same bit without hammer. Hammers with solid heat bits gave ROP increases at least five-fold over the unaided roller bit. Rates of penetration for all tools in Sierra White Granite and drill string torque and axial forces for hammers with roller bits are presented and discussed.

To investigate the feasibility of using non-gaseous drilling fluids, an experimental liquid-powered hammer with a roller bit and a commercial solid-bit mining hammer powered by aqueous foam were tested. Penetration performance and operating characteristics of these tools are described.

The results of gauge wear experiments done at Colorado School of Mines under contract to Sandia National Laboratories are described and are compared to gauge wear observed in the penetration tests of commercial solid bits.

Commercial hammers were tested at high temperature first in factory condition and then with vulnerable parts redesigned for hot operation. A commercial hammer with minor modifications was operated for 15 hours at temperatures from 350-450°F.

STATE OF THE ART OF DRILLING THRUSTERS, SAND79-7129, D. W. Dareing, Maurer Engineering, under contract to Sandia National Laboratories.

This study identifies several different concepts for applying force or thrust to drill bits. Some are fully developed and operational. Most are not. Present day directional wells are being successfully drilled using drill collars, stabilizers, and bent subs. As measurements-while-drilling technology advances it will be desirable to have more direct control of axial and transverse bit force components, which can be controlled at the surface. Hydraulic bit thrusters are a prime candidate for futuristic downhole directional drilling assemblies. While they are not commonly used today, they are fully developed based on twenty years of engineering and field testing.

The selection of drilling thruster type depends on performance requirements and compatibility with other bottomhole equipment.

Future directional drilling assemblies will no doubt include downhole monitoring and telemetry subsystems giving instantaneous feedback to the driller. Future drilling thrusters should therefore be controllable from the surface to allow the driller to change the course of the drill bit as downhole information is transmitted to the rig.

Further studies on drilling thrusters should be combined with design studies of bottomhole drilling assemblies which utilize recent advances in downhole monitoring and telemetry.

FEASIBILITY STUDY OF TUNED-RESONATOR, PULSATING CAVITATING WATER JET FOR DEEP-HOLE DRILLING, SAND81-7126, Virgil E. Johnson, Jr., Wm. T. Lindenmuth, Andrew F. Conn, Gary S. Frederick, Hydro-nautics, Inc., under contract to Sandia National Laboratories.

This study presents the advantages of pulsing a submerged jet to increase its erosion capability (particularly as caused by cavitation) in augmenting deep-hole drill bits. Various methods of accomplishing the pulsation are presented and discussed. The most attractive systems uncovered are acoustic oscillators which passively accomplish pulsations in the flow at frequencies corresponding to a Strouhal number in the range of 0.2 to 1.0. Such passive oscillators are assessed to be feasible candidates for development into practical deep hole drill bit systems and a long-range plan for this research and development is presented and discussed.

EVALUATION OF CAVIJET CAVITATING JETS FOR DEEP-HOLE ROCK CUTTING, SAND81-7067, A. F. Conn, V. E. Johnson, Jr., H. L. Liu, G. S. Frederick, Hydronautics, Inc., under contract to Sandia National Laboratories.

A feasibility study has shown that the Cavijet cavitating fluid jet method should be capable of successfully augmenting the cutting action of mechanical bits under deep-hole conditions. Increased rock cutting rates by existing cavitating jet nozzles can be anticipated with conventional rig pressures for hole depths of at least 1200 m (4000 ft) and possibly deeper. Improved rates of penetration, based on preliminary laboratory roller bit tests, should be achieved by simply substituting Cavijet nozzles absorbing equivalent hydraulic power for conventional roller bit nozzles.

B. Fluid Technology

POWER-LAW RHEOLOGY AND FLOW BEHAVIOR OF LOW INVASION CORING FLUIDS, SAND80-0933, Patrick L. McGuire, Sandia National Laboratories.

An improved pressure coring system has been developed in which an extremely viscous polymer mud is extruded by the core and is used to seal and protect the core from flushing by drilling fluids. The polymer mud must be extremely viscous to minimize invasion, yet must be extruded through a long, narrow annular gap with a minimum of pressure buildup. A highly non-Newtonian shear-thinning polymer is utilized in the low invasion coring fluid. This paper describes the measurement and modeling of non-Newtonian rheology from rotary viscometer data in detail since the simplified equations which are generally used with these instruments can be grossly in error. The development of both an approximate analytical solution and an exact numerical solution of the non-Newtonian extrusion process is presented. These solutions were used to optimize the non-Newtonian rheology of the low-invasion fluid which will be used in actual coring operations.

THE USE OF AN INERT DRILLING FLUID TO CONTROL DRILL PIPE CORROSION, SAND80-1704C, B. C. Caskey and K. S. Copass, Sandia National Laboratories, Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

The results of a geothermal drill pipe corrosion field test are presented. When a low-density drilling fluid was required for drilling a geothermal well because of an underpressured, fractured formation, two drilling fluids were alternately used to compare drill pipe corrosion rates. The first fluid was an air-water mist with corrosion control chemicals. The other fluid was a nitrogen-water mist without added chemicals. The test was conducted during November 1980 at the Baca location in northern New Mexico.

Data from corrosion rings, corrosion probes, fluid samples and flow line instrumentation are plotted for the ten-day test period. It is shown that the inert drilling fluid, nitrogen, reduced corrosion rates by more than an order of magnitude. Test setup and procedures are also discussed.

Development of an on-site inert gas generator could reduce the cost of drilling geothermal wells by extending drill pipe life and reducing corrosion control chemical costs.

RECENT DEVELOPMENTS IN GEOTHERMAL DRILLING FLUIDS, James R. Kelsey and Peter B. Rand, Sandia National Laboratories; M. J. Nevins, W. R. Clements, and L. W. Hilscher, NL Baroid, Inc.; L. J. Remont, G. W. Matula, and D. N. Bailey, Mudtech, Inc., Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

In the past, standard drilling muds have been used to drill most geothermal wells. However, the harsh thermal and chemical environment and the unique geothermal formations have led to such problems as excessive thickening of the fluid, formation damage, and lost circulation. This paper describes three recent development efforts aimed at solving some of these drilling fluid problems. Each of the efforts is at a different stage of development. The Sandia aqueous foam studies are still in the laboratory phase, NL Baroid's polymeric deflocculant is soon to be field tested, and the Mudtech high-temperature mud was field tested several months ago.

REACTIONS OF ATTAPULGITE AND SEPIOLITE IN HIGH-TEMPERATURE DRILLING FLUIDS, Necip Guven, Leroy L. Carney, and Li-Jein Lee, Texas Tech University under contract to Sandia National Laboratories, Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

The fibrous clay minerals attapulgite and sepiolite have been subjected to hydrothermal reactions between 149°C (300°F) and 427°C (800°F). A 4% suspension of each of these clays was autoclaved for 16 to 24 hours with and without the addition of salts of NaCl and KCl at 1% concentration. These fibrous clay minerals start to convert at 204°C (400°F) to a smectite with a lamellar morphology. In fact, attapulgite converts more readily than sepiolite, and the attapulgite-to-smectite transformation is fully completed at 316°C (600°F), whereas 20-50% of the sepiolite remains intact at this temperature. The conversion of the fibrous double- and triple-chain silicates of attapulgite and sepiolite to a layered silicate, such as smectite, favorably affects the rheology of the drilling fluids based on these clays. The mechanism of the conversion is, however, different for these fibrous clays. Attapulgite dissolves first and then smectite precipitates whereas this mechanism takes place for sepiolite at 316°C (600°F). Both attapulgite and sepiolite, and their reaction products, have been examined with an analytical electron microscope (JEM-100CX) in TEM, STEM, SEM, and SAD modes. The intensities of the characteristic X-ray spectra for the elements Mg, Al, Si, Fe, Ca, and K are measured. These observations indicate that 1) significant chemical differences exist between the fibrous clays and the smectites formed from them, and 2) morphological features of the smectites vary with the temperature and with the presence of the salts in the system.

USE OF AN INERT DRILLING FLUID TO CONTROL GEOTHERMAL DRILL PIPE CORROSION, SAND80-1726C, Billy C. Caskey, Sandia National Laboratories, Corrosion/81, The International Corrosion Forum sponsored by the National Association of Corrosion Engineers, April 6-10, 1981, Toronto, Ontario, Canada.

The results of a geothermal drill pipe corrosion field test are presented. When a low-density drilling fluid was required for drilling a geothermal well because of an underpressured, fractured formation, two drilling fluids were alternately used to compare drill pipe corrosion rates. The first fluid was an air-water mist with corrosion control chemicals. The other fluid was a nitrogen-water mist without added chemicals. The test was conducted during November 1980 at the Baca location in Northern New Mexico, USA. Data from corrosion rings, corrosion probes, fluid samples, and flow line instrumentation are plotted for the ten-day test period. It is shown that the inert drilling fluid (nitrogen) reduced corrosion rates by more than an order of magnitude. Test setup and procedures are also discussed. Development of an on-site inert gas generator could reduce the cost of drilling geothermal wells by extending drill pipe life and reducing corrosion control chemical costs.

AN EXPERIMENTAL INVESTIGATION OF LOW INVASION CORING FLUIDS, SAND80-2161, A. A. Heckes and S. M. Delgado, Sandia National Laboratories, SPE/DOE Second Joint Symposium on Enhanced Oil Recovery, April 5-8, 1981, Tulsa, Oklahoma.

A program is underway 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 grey 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 very 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. The importance of CaCO_3 particle size distributions in a low invasion fluid is illustrated in scanning electron microscope photographs.

POLYMER FLUIDS FOR IMPROVED CORES, SAND81-0507, A. A. Heckes, S. M. Delgado, A. L. McFall, Sandia National Laboratories, 56th Annual Technical Conference and Exhibition, Society of Petroleum Engineers, October 4-7, 1981, San Antonio, Texas.

Polymer fluids are presently being adapted for field use to reduce the mud filtrate invasion of cores during the coring process. These fluids encapsulate the core to reduce washing by the drilling fluid and to aid in preserving the in situ fluids content of the core. Development of the fluids continues through modifications tested in the field and through laboratory experimentation. This paper presents a short history of early developmental work which includes the setting of selection criteria, screening potential candidate materials, and selection of a calcium chloride brine/hydroxyethyl cellulose (HEC) polymer/calcium carbonate particle system as the one which best fit the criteria. The current work is also described which involves a laboratory matrix study to determine the optimum commercially available calcium carbonate materials for use under static or dynamic drilling conditions and formations with different permeability.

CORROSION INHIBITION BY CONTROL OF GAS COMPOSITION DURING MIST DRILLING, SAND81-0973, Thomas E. Hinkebein, Tracy L. Snyder, Sandia National Laboratories.

Chemical compositional specifications have been generated for inert gases which reduce drill string corrosion when used in conjunction with mist drilling processes. These specifications are based on the assumption that the corrosion rate is dependent on the dissolved gaseous species concentrations. Data taken both from the literature and from a mist drilling field test with nitrogen in Valle Grande, New Mexico, relate corrosion rates to fluid compositions. These solution compositions are then associated with gas phase compositions using equilibrium data available from the literature and material balances.

DOWNHOLE TEMPERATURE PREDICTION FOR DRILLING GEOTHERMAL WELLS, R. F. Mitchell, Enertech Engineering and Research Co., under contract to Sandia National Laboratories, Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

Unusually high temperatures are encountered during drilling of a geothermal well. These temperatures affect every aspect of drilling, from drilling fluid properties to cement formulations. Clearly, good estimates of downhole temperatures during drilling would be helpful in preparing geothermal well completion designs, well drilling plans, drilling fluid requirements, and cement formulations. The thermal simulations in this report

were conducted using GEOTEMP, a computer code developed under Sandia National Laboratories contract and available through Sandia. Input variables such as drilling fluid inlet temperatures and circulation rates, rates of penetration, and shut-in intervals were obtained from the Imperial Valley East Mesa Field and the Los Alamos Hot Dry Rock Project. The results of several thermal simulations are presented, with discussion of their impact on drilling fluids, cements, casing design, and drilling practices.

A THERMAL ANALYSIS OF DEEP WELLBORE DRILLING AND COMPLETION IN CONDUCTION-DOMINANT HIGH TEMPERATURE REGIMES, SAND81-0499A, Alfonso Ortega and Vance L. Behr, 1981 SPE Annual Technical Conference and Exhibition, October 4-7, 1981, San Antonio, Texas.

The feasibility of drilling relatively deep boreholes in very hot formations has received attention both for the potential of tapping vast quantities of thermal energy in intrusive magma bodies and for scientific exploration of deep continental regions. Whereas holes have been drilled to depths of 10 km with maximum temperatures as high as 200°C, it is a major technological challenge to drill to these depths in high temperature thermal regions. A proposed drilling and completion scenario has been analyzed using a finite difference model of the coupled wellbore-formation energy equations to assess the practicability of drilling and completing a 7 km well to a magmatic zone at 900°C. Water was used as the drilling fluid and the formation heat transfer was assumed to be conduction dominated. Calculations were made for depths of 4.5 and 7 km, with corresponding maximum undisturbed temperatures of 500 and 900°C with results indicating that maximum wellbore temperatures during stable single-phase fluid circulation of 1000 gpm can be maintained below 200 and 370°C respectively. Typical times to achieve pseudo-steady borehole temperatures are found to be on the order of 24 hours during circulation cooling and 36 hours during shut-in reheating. It is observed that regaining stable circulation after shut-in periods of this length will be extremely difficult due to enormous borehole heat fluxes and that a loss of circulation could produce explosive and disastrous phenomena. Thus, although it is theoretically possible to adequately cool deep hot boreholes, initiating and maintaining flow will be dangerous and quite possibly an unstable operation.

C. Borehole Mechanics

LABORATORY EVALUATION OF POLYURETHANE FOAM FOR GEOTHERMAL LOST CIRCULATION PLUGGING, SAND81-7227, Emil Tschoepe, III, Southwest Research Institute, under contract to Sandia National Laboratories.

To evaluate polyurethane foam formulations for use in plugging hot (such as geothermal) formations when lost circulation is encountered during drilling, laboratory tests of three foams were performed. Foams were mixed at high temperature (up to 300°F) and high pressure (up to 900 psig); the mechanical and fluid loss properties of the foams were subsequently determined. The results show that polyurethane foams can be mixed at down-hole conditions and yield acceptable plugging properties.

RESPONSE OF GEOTHERMAL WELL CASING TO CYCLIC THERMAL HISTORIES, SAND81-0553, D. L. Wesenberg, C. M. Stone, Sandia National Laboratories, 56th Annual Technical Conference and Exhibition, Society of Petroleum Engineers, October 4-7, 1981, San Antonio, Texas.

Geothermal well casing is subjected to high temperature environments not typically encountered in conventional oil and gas completions. The high temperatures create problems which are not readily addressed by using conventional casing design techniques. In particular, the problem of analyzing casing with temperature dependent material properties undergoing complex thermal loading is one requiring more than standard strength of material approaches. This paper describes the casing structural analysis for a geothermal well subjected to a cyclic thermal history. The effects of this cyclic loading on casing integrity will be discussed and a description will be given of the state-of-the-art finite element programs used to investigate this problem. Results are obtained which show the stress state in the casing as a function of time. By studying this changing stress state, detailed information about the loading experienced by the casing can be used to adequately design casing for the expected thermal environment.

MECHANISMS OF FORMATION DAMAGE IN MATRIX PERMEABILITY GEOTHERMAL WELLS, J. L. Bergosh, R. B. Wiggins, D. O. Enniss, and A. H. Jones, Terra Tek, Inc., under contract to Sandia National Laboratories, Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

Matrix permeability geothermal formations are subject to damage during well drilling and completion. Near wellbore permeability

impairment that may occur as a result of particulate invasion, and chemical interaction between formation clays, drilling mud filtrates and formation brines is investigated.

Testing of various filtration chemistries on the permeability of East Mesa sandstone indicates that permeability is significantly impaired by the flow of low salinity formation brines. This damage is attributed to cation exchange and removal processes which alter the stability of clay structures. Fluid shearing dislodges particles, which clog pore throats, irreversibly reducing permeability.

The test program investigating the effects of mud-transported particles on geothermal formations is still in progress. The rationale, apparatus and test procedures are described. Final results of this testing will be presented at the conference.

TEMPERATURE HISTORIES IN GEOTHERMAL WELLS -- SURVEY OF ROCK THERMO-MECHANICAL PROPERTIES AND DRILLING, PRODUCTION, AND INJECTION CASE STUDIES, SAND81-7128, Malcolm A. Goodman, Enertech, under contract to Sandia National Laboratories.

Thermal and mechanical properties for geothermal formations are tabulated for a range of temperatures and stress conditions. Data was obtained from the technical literature and direct contacts with industry. Thermal properties include heat capacity, conductivity, and diffusivity. Undisturbed geothermal profiles are also presented. Mechanical properties include Young's modulus and Poisson ratio.

GEOTEMP thermal simulations of drilling, production and injection are reported for two geothermal regions, the hot dry rock area near Los Alamos and the East Mesa field in the Imperial Valley. Actual drilling, production, and injection histories are simulated. Results are documented in the form of printed GEOTEMP output and plots of temperatures versus depth, radius, and time. Discussion and interpretation of the results are presented for drilling and well completion design to determine: 1) wellbore temperatures during drilling as a function of depth, 2) bit temperatures over the drilling history, 3) cement temperatures from setting to the end of drilling, and 4) casing and formation temperatures during drilling, production, and injection.

MECHANISMS OF FORMATION DAMAGE IN MATRIX PERMEABILITY GEOTHERMAL WELLS, SAND81-7208, J. L. Bergosh, et al., Terra Tek, Inc., under contract to Sandia National Laboratories.

"Formation damage" is a term used throughout the industry to describe negative interaction between the drilling operation and the producing formation(s) resulting in an impaired near wellbore permeability and subsequent reduction in production. In geothermal wells, where economic viability is predicated upon the production of large amounts of hot water and/or steam, formation damage must be understood, controlled and minimized. Formation damage is a complex problem and no unique, definitive solution exists at present. Numerous researchers have addressed various aspects of this problem, generally from the perspective of oil/gas production. Solutions and understandings so generated have not always had successful transitions to geothermal applications. The mechanisms of geothermal formation damage discussed in this report are divided into three major categories: mud filtrate induced damage, low salinity formation brine effects, and particulate induced damage. Most prior laboratory testing has focused upon matrix permeability dominated reservoirs such as East Mesa. However, a large portion of geothermal resources depend upon fractures for their primary production; therefore, it is necessary to simulate fractured formations in the laboratory to properly assess the interaction of drilling fluids with many geothermal formations. A final section in this report discusses the best methods of simulating a naturally occurring fracture in the laboratory.

LOST CIRCULATION EXPERIENCE IN GEOTHERMAL WELLS, Malcolm A. Goodman, Enertech Engineering and Research Co., under contract to Sandia National Laboratories, Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

Lost circulation during drilling and cementing in geothermal wells is a problem common to most geothermal areas. Material and rig time costs due to lost circulation often represent one fourth or more of the total well cost. Assessment of the general drilling and completion practices commonly used for handling lost circulation have been surveyed and evaluated under a study sponsored by Sandia National Laboratories. Results of this study, including interviews with geothermal production companies and with drilling fluid service companies, are reported in the paper.

BALANCED PRESSURE TECHNIQUES APPLIED TO GEOTHERMAL DRILLING, SAND81-1502C, James R. Kelsey, Sandia National Laboratories, and Don W. Dareing, Maurer Engineering Inc., Geothermal Resources Council 1981 Annual Meeting, October 25-29, 1981, Houston, Texas.

Geothermal drilling often takes place in high surface relief areas where ground water tables are a considerable distance (approximately 1000 ft) below rig level. Above the water table, the formation pressure gradient is zero, and below the water table, the formation pressure increases with depth. Pressure unbalance between wellbore drilling fluid and formation pressures exists from spud-in and drives drilling fluid into the formation when voids are encountered at the drill bit. When this happens, drilling fluid does not return to the rig because it is pumped into these voids and thus circulation of the drilling fluid is lost.

Lost circulation is generally controlled by two techniques: 1) sealing formations so that drilling fluid will not flow into them, and 2) reducing drilling fluid pressure in the wellbore so that it essentially balances formation fluid pressure. This paper deals with the second control technique, describing four balanced pressure drilling techniques and giving advantages and disadvantages of each. It is based on a study directed by Sandia National Laboratories.

BALANCED PRESSURE TECHNIQUES APPLIED TO GEOTHERMAL DRILLING, SAND81-7130, Don W. Dareing, Maurer Engineering, under contract to Sandia National Laboratories.

Geothermal drilling often takes place in high surface relief areas where ground water tables are a considerable distance (1,000 ft) below rig level. Above the water table, formation pore pressure is zero. Below the water table, formation pore pressure increases with depth at a rate depending on formation temperature. Pressure unbalance between wellbore drilling fluid into the formation when voids are encountered at the drill bit. When this happens, portions or all of the drilling fluid does not return up the drill pipe/wellbore annulus to the rig, instead it flows into the voids. Thus, the term "lost circulation."

LOST CIRCULATION IN GEOTHERMAL WELLS -- SURVEY AND EVALUATION OF INDUSTRY EXPERIENCE, SAND81-7129, Malcolm A. Goodman, Enertech Engineering and Research Co., under contract to Sandia National Laboratories.

Lost circulation during drilling and completion of geothermal wells can be a severe problem, particularly in naturally fractured and/or vugular formations. Geothermal and petroleum

operators, drilling service companies, and independent consultants were interviewed to assess the lost circulation problem in geothermal wells and to determine general practices for preventing lost circulation. This report documents the results and conclusions from the interviews and presents recommendations for needed research. In addition, a survey was also made of the lost circulation literature, of currently available lost circulation materials, and of existing lost circulation test equipment.

EVALUATION OF EQUIPMENT AND METHODS TO MAP LOST CIRCULATION ZONES IN GEOTHERMAL WELLS, SAND80-7057, W. J. McDonald, et al., Maurer Engineering, under contract to Sandia National Laboratories.

The purpose of this study is to assess the capability of equipment and methods to map and quantify lost circulation zones in geothermal wells. A comprehensive list and explanation of the tools available for this purpose is included.

D. Diagnostic Technology

ACOUSTIC CEMENT BOND LOGGING DIAGNOSTICS FOR GEOTHERMAL APPLICATIONS, Hsi-Tien Chang, Sandia National Laboratories, Geothermal Resources Council 1981 Meeting, October 25-29, 1981, Houston, Texas.

For the successful and safe operation of a geothermal well, casing and cement conditions must be accurately determined. Cement bond logs are needed to detect channels or water pockets in the cement between the pipe and the formation and to determine the condition of the cement bond to the pipe and to the formation. Instrumentation for making such measurements is limited by the temperature capabilities ($<175^{\circ}\text{C}$) of existing logging equipment which was developed for the oil and gas industry. This paper reviews an acoustic system of the type that is needed for geothermal cementing inspection, identifies the principle deficiencies in its high temperature use, and describes Sandia's R&D project for developing high temperature acoustic cement bond logging diagnostics.

A HIGH-TEMPERATURE ACOUSTIC BOREHOLE TELEVIEWER, F. E. Heard and T. J. Bauman, Sandia National Laboratories, Proceedings -- High Temperature Electronics and Instrumentation Conference -- December 1981, p. 177.

Geothermal producers have long expressed a need for high temperature fracture mapping capability. The acoustic borehole televiewer has been shown to be the most useful tool for determining location, orientation, and characterization of fractures as they intersect the borehole. However, it has not been capable of operation at geothermal temperatures. This report describes an effort conducted at Sandia National Laboratories to develop a televiewer for operation in a geothermal environment. Theory of operation, design methods, and test results are discussed. The Sandia televiewer has operated successfully at a temperature of 275°C and pressure of 4500 psi.

GaP SCHOTTKY DIODES FOR HIGH TEMPERATURE APPLICATIONS, M. H. Weichold and O. Eknayan, Texas A&M, and J. A. Coquat, Sandia National Laboratories, Proceedings of IEEE Conference, May 11-13, 1981, Atlanta, Georgia.

A need for high temperature electronic components has been established. In an effort to meet part of this need, four metals have been evaluated for use in fabricating a Schottky barrier diode. Schottky diodes made from Pt, Cr, Al and Ni were aged for 1000 hours at 275°C . These devices were evaluated considering the barrier height, ϕ_{bn} , and leakage current

density, J_1 , as a function of aging time. Results indicate that the devices are dominated by a large surface state density which is partially compensated by prolonged aging. Nickel Schottky diodes emerge as the most stable devices.

THICK FILM MATERIALS AND DISCRETE PASSIVE COMPONENTS, R. W. Vest, Purdue University, under contract to Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981, p. 69.

Thick film materials and discrete passive components have the potential of maintaining constant properties to temperatures well above their normal use range. Since thick film hybrids and add-on capacitors are typically processed at temperatures of 800°C and above, it might be expected that they would perform satisfactorily at temperatures up to 500°C. However, this is not necessarily true because thick film resistors and capacitors represent systems which are not in thermodynamic equilibrium, and are optimized for use in a lower temperature range, typically -55 to 125°C. Many of the 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 high temperature. This paper will discuss the use of commercially available materials and components, and also the status of thick film systems developed specifically for use at high temperatures.

GALLIUM PHOSPHIDE DEVICES, O. Eknayan, W. B. van der Hoeven and M. H. Weichold, Texas A&M University, under contract to Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

The need for high temperature semiconductor devices is well established and is spurred by expanding demands for high temperature electronic instrumentations in a number of specialized systems. In an effort to meet some of the demands in the area of geothermal well logging, work has been undertaken to develop gallium phosphide, GaP, devices functional over the 275-300°C temperature range for prolonged times of operation (1000 hours). The choice of GaP as the semiconductor material was governed by its 2.24 eV energy bandgap. This is large relative to that of the two other widely used semiconductor materials, silicon (1.12 eV) and gallium arsenide (1.43 eV). While other binary compound semiconductor materials are known to have wider energy bandgaps, e.g., SiC (3 eV) and ZnS (3.6 eV), their limited availability and processing technology hinders their use. The use of large energy bandgap material is essential to prevent intrinsic limitations related to thermal

carrier generation which degrades the effective operation of devices at high temperatures.

The investigations in this work specifically addressed the formation of reliable ohmic contacts, and Schottky diodes, plus the fabrication and demonstration of transistor action by means of GaP MESFET (Metal Schottky Field Effect Transistor) devices.

COMPOUND SEMICONDUCTORS FOR HIGH-TEMPERATURE ELECTRONIC APPLICATIONS, T. E. Zipperian and R. J. Chaffin, Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

Compound semiconductor technology is reviewed as it relates to high-temperature electronic device applications. The electrical requirements of majority and minority carrier device types are examined and six compound semiconductor materials are presented which are capable of operation above 300°C. The state of the technological development of each of these materials is then reviewed, and several potential application areas of compound semiconductors are suggested. Finally, the high-temperature characteristics of devices fabricated in four of these chemical systems are displayed, and conclusions are drawn on the near-term commercialization of this technology.

AMORPHOUS METAL DIFFUSION BARRIERS, K. J. Guo, J. D. Wiley, J. H. Perepezko, J. E. Nordman, D. B. Aaron, E. A. Dobisz, D. E. Madisen, and R. E. Thomas, University of Wisconsin, under contract to Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

As semiconductor devices have been required to operate at ever-increasing temperatures, it has become apparent that existing metallization systems pose severe reliability problems, causing device failures through a variety of diffusion and inter-diffusion-related mechanisms. Attempts to retard these failures have usually focused on the incorporation of thin diffusion-barrier layers within the metallization system. In the previous High Temperature Electronics Conference we pointed out that conventional polycrystalline diffusion barriers are unlikely to afford more than a very modest extension of the safe operating temperatures, as grain boundaries in the barrier layers provide efficient inter-diffusion paths. Pursuing this reasoning, we proposed the use of amorphous metal films as primary metallizations (requiring no separate barrier layers) or as diffusion barriers in an otherwise conventional metallization system. Initial work showed that carefully selected amorphous

alloys having high crystallization temperatures do, indeed, exhibit exceptionally low diffusivities. In this paper, we present further experimental evidence of the effectiveness of amorphous metal films as diffusion barriers between Au or Cu overlayers and Si, GaAs, or GaP substrates.

MATERIALS AND INTERFACES FOR HIGH TEMPERATURE MOS AND CMOS COMPONENTS, John D. McBrayer, Bruce L. Draper, Sandia National Laboratories, and Dick Swanson, Stanford University, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

In previous work it was shown that the silicon planar technology is suitable for high temperature applications. In those investigations, it was found that a major problem in the use of bulk CMOS devices at elevated temperatures was high leakage current through input protection diodes and p-well/substrate isolation junctions. To reduce these problems, a dielectrically isolated CMOS process was developed at Harris Semiconductor. Although the recent success of such projects is encouraging, there is concern over the long-term reliability of high temperature MOS technologies. Interactions at the metal/SiO₂ or Si/SiO₂ interfaces could cause threshold shifts large enough to initiate depletion mode operation in normally enhancement mode devices, or simply shift operating characteristics sufficiently to render circuits inoperable. In this paper, results of initial aging tests on high temperature CMOS components will be presented. Auger profiling of aged and unaged MOS capacitors will also be presented along with a discussion of possible deleterious effects of high temperature operation.

RADIATION AND TEMPERATURE TOLERANT HYBRIDS, D. W. Palmer and B. L. Draper, Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

The nuclear and space industries require electronics with higher tolerance to radiation than that commercially available. The recently developed 300°C electronics technology based on junction field-effect transistors and thick film hybridization was tested beyond 10⁹ rad (Si) in a cobalt 60 gamma source and 10¹⁶ neutrons/cm² in an annular core reactor. Circuits and individual components from this technology all survived these total doses although often required annealing at 200°C or 300°C to regain functionality. Radiation tolerance comparisons were made with military radhard CMOS, simplified linear I²L, and JFET technologies. Real time 200-300°C annealing should allow circuit functionality to even higher radiation levels.

COMMERCIAL 200-275°C HYBRIDS, Suguna Gopal, Teledyne Philbrick, under contract to Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

This paper outlines the design and development of high temperature hybrids and some of the problems encountered in producing electrically and mechanically reliable hybrids at 275°C. Initial mechanical and electrical failures have led to the development of better fabricating techniques and better methods of pre-testing and characterizing active components. Hybrid components for geothermal logging instrumentation were the first 275°C hybrids that were developed commercially.

HIGH-TEMPERATURE GEOTHERMAL CABLEHEADS, Joe A. Coquat, Richard W. Eifert, Sandia National Laboratories, SAND81-2542.

Two high-temperature, corrosion-resistant logging cableheads which use metal seals and a stable fluid to achieve proper electrical terminations and cable-sonde interfacing are described. A tensile bar provides a calibrated yield point, and a cone assembly anchors the cable armor to the head. Electrical problems of the sort generally ascribable to the cable-sonde interface were absent during demonstration hostile-environment loggings in which these cableheads were used.

DEVELOPMENT OF A METAL SHEATH CABLE, Arthur S. Halpenny, Halpen Engineering, Inc., and Stanley J. Gray, Manufacturing Innovations Co., under contract to Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

Our concept was to utilize an existing product which we refer to as the core cable. Figure 1 shows a single conductor cable. The conductor is surrounded by mineral insulation and contained with an outer metal jacket. This general configuration has been commercially available for over 15 years. It is marketed in numerous specifications, depending on the application. Applications range from instrumentation purposes, to heating cables, to power cables. In this configuration the cable will not meet the requirements of geothermal logging cable for two major reasons: 1) continuous lengths to 15,000 feet are not practical from a raw material limits standpoint and from a manufacturing process standpoint, and 2) its breaking strength would have to be substantially improved. Both problems have been resolved by special splicing techniques and by reinforcing the core cable with multiple sheaths. Several thousand feet of geothermal logging cable have now been produced.

FABRICATION OF A 275°C GEOTHERMAL TEMPERATURE TOOL, Peggy Ann Bonn, Sandia National Laboratories, Proceedings-High Temperature Electronics and Instrumentation Conference-December 1981.

This paper reviews the fabrication of a Prototype 275°C Geothermal Temperature Tool. This tool fabrication uses hybrid circuits which were developed at Sandia National Laboratories and are now being built at Teledyne Philbrick. To achieve high-temperature operation, the standard military specification hybrid technology was modified in fabrication processes and materials.

SOURCEBOOK ON HIGH-TEMPERATURE ELECTRONICS AND INSTRUMENTATION, Anthony F. Veneruso, Editor, Sandia National Laboratories, SAND81-2112.

This sourcebook summarizes the high-temperature characteristics of a number of commercially available electronic components and materials required in geothermal well-logging instruments that must operate to 275°C. The sourcebook is written to provide a starting place for instrument designers, who need to know the high-temperature electronic products that are available and the design and performance limitations of these products. The electronic component information given includes the standard repertoire of passive devices such as resistors, capacitors, and magnetics; the active devices and integrated circuits sections emphasize silicon semiconductor JFETs and CMOS circuits; and, to complete the electronics, interconnections and packaging of hybrid microelectronics are described. Thermal insulation and refrigeration alternatives are also presented in the sourcebook. Finally, instrument housing materials and high-temperature cables and cablehead connectors are listed. This information was compiled as part of the Geothermal Logging Instrumentation Development Program that Sandia National Laboratories conducted for the U. S. Department of Energy's Division of Geothermal Energy from 1976 to 1981.

PROCEEDINGS-HIGH TEMPERATURE ELECTRONICS AND INSTRUMENTATION CONFERENCE, SAND82-0425, Sandra R. Hudson and James R. Kelsey, Editors, Sandia National Laboratories.

This report presents the results of a two-day conference which reviewed the state-of-the-art and recent progress in High Temperature Electronics and Instrumentation. The meeting was held at the Marriott at the Astrodome in Houston, Texas, December 7-8, 1981, and was sponsored by Sandia National Laboratories in conjunction with the U. S. Department of Energy, the University of Houston, and the IEEE. Over 300 attendees participated in this seminar which had sessions on Electronic Devices, Hybrid Microelectronics, 200°C Commercial Hybrids,

and High Temperature Logging Cables and Package Materials. In addition to the technical sessions, industry participants exhibited their latest materials and components. This meeting was essentially a "graduation" exercise since Sandia National Laboratories and the Department of Energy have essentially completed their program in the High Temperature and Instrumentation Program; this conference served as a vehicle to transfer this technology to industry participants.

E. Systems Analysis/Program Summaries

GEOTHERMAL WELL COSTS AND THEIR SENSITIVITIES TO CHANGES IN DRILLING AND COMPLETION OPERATIONS, C. C. Carson and Y. T. Lin, Sandia National Laboratories, Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, January 21-23, 1981.

This paper presents a detailed analysis of the costs of drilling and completing geothermal wells. The basis for much of the analysis is a computer-simulation-based model which calculates and accrues operational costs involved in drilling and completing a well. Geothermal well costs are discussed in general, with special emphasis on variations among different geothermal areas in the United States, effects of escalation and inflation over the past few years, and comparisons of geothermal drilling costs with those for oil and gas wells. Cost differences between wells for direct use of geothermal energy and those for electric generation are also indicated. In addition, a breakdown of total well cost into its components is presented. This provides an understanding of the relative contributions of different operations in drilling and completions. A major portion of the cost in many geothermal wells is from encountered troubles, such as lost circulation, cementing difficulties, and fishing. These trouble costs are considered through both specific examples and statistical treatment of drilling and completions problems.

The sensitivities of well costs to variations in several drilling and completion parameters are presented. The model makes it possible to easily vary parameters such as rates of penetration; bit lifetimes; bit, rental, or rig costs; delay times; number of cement plugs; etc. The effects of these variations on different types of geothermal wells are compared.

ECONOMIC EVALUATION OF GEOTHERMAL DRILLING EQUIPMENT, SAND80-7080, Science Applications, Inc., under contract to Sandia National Laboratories, June 1981.

This document provides the necessary data base and the methodology to evaluate certain economic factors of the drilling industry and to economically evaluate, for both need and worth, new solutions to technical problems encountered by the geothermal drilling contractor. This data base and methodology has been incorporated into a FORTRAN code computer program. The program allows the user to choose any one of three different size rigs to be used in the area. The economic data and equipment requirements for the above selection are displayed by the preliminary program output and may be changed as desired. After the model has been changed, the computer program calculates the cash flow requirements to define Discounted

Cash Flow-Return on Investment (DCF-ROI) data, and other economic factors. In addition, two methods for determining Day Rate are displayed. The first method, "Day Rate-Cash Flow Model," defines the day rate needed to obtain a specific return on investment. The second method, "Day Rate-Cost Plus Fee Model," defines the day rate needed to cover estimated daily costs, plus a desired fee/profit. Evaluation of this data, in conjunction with data base changes required for the incorporation of new types of equipment in the drilling system, allows the program user to determine both the need for and the worth of the incorporated equipment.

WELL DESCRIPTIONS FOR GEOTHERMAL DRILLING, SAND81-1491C, C. C. Carson, Sandia National Laboratories and B. J. Livesay, Livesay Consultants, Geothermal Resources Council Annual Meeting, October 25-29, 1981, Houston, Texas.

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

GEOTHERMAL WELLS: A FORECAST OF DRILLING ACTIVITY, SAND81-7127, Gerald L. Brown, A. J. Mansure, and J. M. Miewald, The BDM Corporation, under contract to Sandia National Laboratories.

The report forecasts numbers and problems for geothermal wells expected to be drilled in the United States between 1981 and 2000 AD. The 3800 wells forecasted for major electric power projects (totaling 6 GWe of capacity) are categorized by type (production, etc.), and by location (The Geysers, etc.). 6000 wells are forecasted for direct heat projects (totaling 0.2 Quads per year). Equations are developed for forecasting the number of wells, and data is presented. Drilling and completion problems in The Geysers, The Imperial Valley, Roosevelt Hot Springs, the Valles Caldera, northern Nevada, Klamath Falls, Reno, Alaska, and Pagosa Springs are discussed. Likely areas for near-term direct heat projects are identified.

THE IMPACT OF BIT PERFORMANCE ON GEOTHERMAL WELL COST, Y. T. Lin, Sandia National Laboratories, Geothermal Resources Council, Transactions Vol. 5, October 1981, p. 253.

The impacts of technological improvements in drill bits on geothermal well costs are evaluated using a compilation of well

costs associated with conventional drilling technology. The compilation centers around well models that have been constructed for the major U.S. geothermal areas. Parametric analyses showing the relative importance of the bit performance parameters in well cost reduction and the results of analyses of specific new bit technologies are presented. These results have been used to evaluate the benefits of new technologies and to direct their development.

PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY, SAND81-0036C, co-sponsored by the U. S. Department of Energy, Comision Federal de Electricidad de Mexico, and Sandia National Laboratories, Albuquerque, New Mexico, January 21-23, 1981.

The high cost of drilling and completing geothermal wells is an impediment to the timely development of an important energy resource. This conference was organized to share experiences, problems, and solutions encountered around the world and to make a contribution to decreasing the costs of drilling and completing geothermal wells. Discussions of geothermal well problems should also identify areas of needed technology development. This information will be useful to government and industry planners in defining research and development activities.

GEOPRESSURED GEOTHERMAL DRILLING AND COMPLETIONS TECHNOLOGY DEVELOPMENT NEEDS, SAND81-0021, A. A. Maish, Sandia National Laboratories.

Geopressured geothermal formations found in the Texas and Louisiana Gulf Coast Region and elsewhere have the potential to supply large quantities of energy in the form of natural gas and warm brine (200-300°F). Advances are needed, however, in hardware technology, well design technology, and drilling and completion practices to enable production and testing of exploratory wells and to enable economic production of the resource should further development be warranted. This report identifies needed technology for drilling and completing geopressured geothermal source and reinjection wells to reduce the cost and to accelerate commercial recovery of this resource. A comprehensive prioritized list of tasks to develop necessary technology has been prepared. Tasks listed in this report address a wide range of technology needs including new diagnostic techniques, control technologies, hardware, instrumentation, operational procedure guidelines and further research to define failure modes and control techniques. Tasks are organized into the functional areas of well design, drilling, casing installation, cementing, completions, logging, brine reinjection and workovers.

SANDIA NATIONAL LABORATORIES GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM, SAND81-0321A, James R. Kelsey, Sandia National Laboratories, 10th CATMEC Meeting, sponsored by Southeastern Massachusetts University, February 24-26, 1981, Salt Lake City, Utah.

This presentation describes the progress, status, and results of ongoing research and development within the Geothermal Drilling and Completion Technology Development Program. The work reported is sponsored by the Department of Energy, Division of Geothermal Energy, with program management provided by Sandia National Laboratories. The program emphasizes the development of geothermal drilling hardware, drilling fluids, completion technology, and lost circulation control methods. Advanced drilling systems are also under development. The goals of the program are to develop the technology required to reduce well costs by 25% in the short-term and 50% in the long-term.

A REVIEW OF THE GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM, SAND81-0319C, Donald L. Wesenberg, Sandia National Laboratories, SPE Drilling Study Group, March 19, Houston, Texas.

This presentation describes the progress, status, and results of ongoing research and development within the Geothermal Drilling and Completion Technology Development Program. The work reported is sponsored by the Department of Energy/Division of Geothermal Energy (DOE/DGE), with program management provided by Sandia National Laboratories. The presentation emphasizes projects dealing with Stratapax bits, rock/cutter interactions, bit hydraulics, cavitating jets, wellbore inertial navigation, wellbore circulating temperatures, lost circulation, and drill string dynamics.

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM PLAN, SAND81-0380, Samuel G. Varnado, James R. Kelsey, Donald L. Wesenberg, Sandia National Laboratories.

This document presents a long-range plan for the development of new technology which will reduce the cost of drilling and completing geothermal wells. The role of this program in relation to the total Federal Geothermal Energy Program is defined and specific program goals are identified. Then, the current status of the program, initiated in FY-78, is presented, and research and development activities planned through 1987 are described. Budget and milestone estimates for each task are provided. The management plan for implementing the program is also discussed. The goals of this program are to develop the technology required to reduce the cost of drilling and completing geothermal wells by 25% in the near-term and by 50% in the long-term. Efforts

under this program to date have resulted in new roller bit designs which will reduce well costs by 2-4%, new drag bits which have demonstrated marked increases in penetration rate, and the field verification of the effectiveness of inert drilling fluids in reducing drill pipe corrosion. Activities planned for the next six years for achieving the program goals are described. Technical activities include work in the areas of drilling hardware, drilling fluids, lost circulation control methods, completion technology, advanced drilling systems, and support technology.

GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT, October 1980-December 1980, James R. Kelsey, Editor, SAND81-0381, 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 shown above. The work reported is sponsored by the Department of Energy/Division of Geothermal Energy, with program management provided by Sandia National Laboratories. The program emphasizes the development of geothermal drilling hardware, drilling fluids, completion technology, and lost circulation control methods. Advanced drilling systems are also under development. The goals of the program are to develop the technology required to reduce well costs by 25% in the near-term and by 50% in the long-term.

ACCESSING THE GEOTHERMAL RESOURCE, SAND81-1384, James R. Kelsey, Proceedings of Showcase for Technology, October 28-30, 1981, Albuquerque, New Mexico.

This paper describes the technology development efforts ongoing at Sandia National Laboratories in the areas of drilling, completion, and logging instrumentation. These development efforts are aimed at solving the problems associated with the high temperatures, hard-fractured geological formations, and corrosive formation fluids.

GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT, January 1981-March 1981, James R. Kelsey, Editor, SAND81-1020, 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. The work

reported is sponsored by the Department of Energy, Division of Geothermal Energy, with program management provided by Sandia National Laboratories. The program emphasizes the development of geothermal drilling hardware, drilling fluids, completion technology, and lost circulation control methods as they apply to advanced drilling systems.

THE SANDIA PROGRAM IN GEOTHERMAL TECHNOLOGY DEVELOPMENT, SAND81-1490C, James R. Kelsey and B. C. Caskey, Sandia National Laboratories, Geothermal Resources Council Annual Meeting, October 25-29, 1981, Houston, Texas.

The objective of the Department of Energy sponsored program in geothermal research and development has shifted from demonstrating technologies for well cost reduction to long-range R&D aimed at developing advanced technologies. This paper presents the accomplishments of the program, the status of current projects, and plans for future activities. The program includes R&D in high temperature rock penetration mechanics, drilling fluids, borehole mechanics, and diagnostics technology.

II. MAGMA ENERGY

Introduction

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

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

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

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 Characterization, 4) Materials Compatibility, and 5) Energy Extraction.

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A. Source Location and Definition

MULTIPLE SCALE CONVECTION IN THE EARTH'S MANTLE: A THREE-DIMENSIONAL STUDY, Charles R. Carrigan, Sandia National Laboratories and Bullard Laboratories, Cambridge University, Science 215, pp 965-967, February 1982.

Recent laboratory experiments suggest that a convective regime characterized by two length scales of motion is a reasonable model for circulations in the earth's upper mantle. The flows of largest horizontal scale represent a likely plate driving mechanism required by some theories of plate tectonics. It is also argued that the superposed large and small scales, within the context of current geochemical and mechanical theories, can contribute to the heterogeneity of the upper mantle and crust -- a contradiction of the often assumed role of convection as a mechanism for mixing the mantle.

VESTICULATION OF MAFIC MAGMA DURING REPLENISHMENT OF CRUSTAL MAGMA RESERVOIRS, J. C. Eichelberger, Sandia National Laboratories, Nature 288, (1980) pp 446-450.

Mafic inclusions in andesitic and dacitic lavas and in equivalent plutonic rocks have been interpreted as cumulates from fractional crystallization, restites from deep crustal melting and rapidly crystallized mafic magmatic material generated during magma mixing. The implications of these interpretations for both magmatic and crustal evolution differ dramatically. I have previously argued that the inclusions result from magma mixing on the basis of their texture, bulk composition and phase composition. A new observation is that the inclusions exhibit high vesicularity and consequently have a lower bulk density than their hosts. This property is consistent with generation of the inclusions by magma mixing, and may play an important part in the evolution of large magma reservoirs within the upper crust.

B. Source Tapping

DRILLING INTO MOLTEN ROCK--AN UPDATE, John L. Colp, Sandia National Laboratories, SAND81-0250, Proceedings 1981 Arc Volcanism Symposium, International Association of Volcanology and Chemistry of Earth's Interior, August 28-September 9, 1981, Tokyo, Japan.

The Sandia Magma Energy Research Project is assessing the scientific feasibility of extracting energy directly from buried circulating magma resources (Colp and Stoller, 1981). 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 molten rock sensing experiments performed at Kilauea Iki lava lake, it was necessary to drill a series of holes through the solid upper crust and through the molten zone at that location.

THERMAL GEOPHYSICAL TECHNIQUES FOR LOCATING MAGMA, H. C. Hardee, Sandia National Laboratories, SAND81-0111, Proceedings 1981 Arc Volcanism Symposium, International Association of Volcanology and Chemistry of Earth's Interior, August 28-September 9, 1981, Tokyo, Japan.

Thermal geophysical techniques are useful in defining the depth, areal extent, or state of magma bodies beneath volcanic and geothermal areas. In areas where hydrothermal activity is small, conduction techniques can be used to estimate the size and depth of magma bodies. Analytical conduction solutions have been obtained for simple magma geometries (dikes, sills, spheres) and the results compare favorably with field data from Coso geothermal area, Yellowstone, and Avachinsky volcano where magma bodies are suspected at depths on the order of 5 km. In areas where hydrothermal circulation cannot be ignored, conduction techniques can still be used by taking downhole measurements below the hydrothermal zone. Such techniques have been used in lava lakes in Hawaii and Iceland to predict the areal extent and solidification rate of the underlying magma. Accurate heat flow measurements can be made within hydrothermal circulation zones, although with difficulty. Heat flow in such zones is primarily dependent on the permeability of the zone rather than the condition of the underlying magma. Such measurements do not readily yield information about the depth of the magma although these measurements can be used to determine the areal extent of the magma body.

C. Magma Characterization

RESTORATION OF NEW VOLCANIC GAS ANALYSES FROM BASALTS OF THE AFAR REGION: FURTHER EVIDENCE OF CO₂-DEGASSING TRENDS, T. M. Gerlach, Sandia National Laboratories, Journal of Volcanology and Geothermal Research, Volume 10, No. 1-3 (1981), p. 83.

The restored compositions for approximately 70 new analyses reported recently for Erta Ale lava lake (GeGuern, et al., 1979) are in good agreement with restored compositions (Gerlach, 1979A) based on previously published data. The results confirm earlier indications that gas collections taken at different times from the lava lake are related principally to variations in CO₂ content. Restored compositions for gas samples collected in the final stages of a November 1978 Ardoukoba eruption along the Asal Rift spreading axis resemble the Erta Ale gases except for a much lower CO₂ content. The Ardoukoba gases fall close to a CO₂-decreasing control line for gases with initial compositions similar to the 1971-73 Erta Ale gases. These results suggest that gases released from basaltic lava along zones of crustal spreading follow compositional trends dominated by changes in CO₂ content.

CHEMICAL CHARACTERISTICS OF THE VOLCANIC GASES FROM NYIRAGONGO LAVA LAKE AND THE GENERATION OF CH₄-RICH FLUID INCLUSIONS IN ALKALINE ROCKS, T. M. Gerlach, Sandia National Laboratories, Journal of Volcanology and Geotheram Research, 8(1980)177-189.

Methods used previously to remove compositional modifications from volcanic gas analyses for Mounta Etna and Erta' Ale lava lake have been employed to estimate the gas phase composition at Nyirangongo lava lake, based on samples obtained in 1959. H₂O data were not reported in 11 of the 13 original analyses. The restoration methods have been used to estimate the H₂O contents of the samples and to correct the analyses for atmospheric contamination, loss of sulfur and for pre- and post-collection oxidation of H₂S, S₂, and H₂. The estimated gas compositions are relatively CO₂-rich, low in total sulfur and reduced. They contain approximately 35-50% CO₂, 45-55% H₂O, 1-2% SO₂, 1-2% H₂, 2-3% CO, 1.5-2.5% H₂S, 0.5% S₂, and 0.1% COS over the collection temperature range 1020 to 960°C. The oxygen fugacities of the gases are consistently about half an order of magnitude below quartz-magnetite-fayalite. The low total sulfur content and resulting low atomic S/C of the Nyiragongo gases appear to be related to the relatively low f_{O₂} of the crystallizing lava. At temperatures above 800°C and pressures of 1-1.5 kbar, the Nyiragongo gas compositions resemble those observed in primary fluid inclusions believed to have formed at similar temperatures and pressures in nephelines of intrusive alkaline rocks. Cooling to 300°C, with f_{O₂} buffered by the rock, results in gas compositions very rich in CH₄.

(50-70%) and resembling secondary fluid inclusions formed at 200-500°C in alkaline rocks. Below 600°C the gases become supersaturated in carbon as graphite. These inferences are corroborated by several reports of hydrocarbons in plutonic alkaline rocks, and by the presence of CH₄-rich waters in Lake Kivu -- a lake on the flanks of Nyiragongo volcano.

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), p. 191.

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% H₂O, 1-10% CO₂, 2-4% SO₂, 1.5-3% H₂, 0.1-0.7% CO, 0.1-0.9% H₂S and 0.01-0.25% S₂. O₂ fugacities are approximately on the quartz-magnetite-fayalite buffer at the collection temperature. CO₂ appears to decrease over the period 1964 to 1967, suggesting a progressive decrease in the CO₂ concentration of the erupting melt. The water-rich gas compositions are consistent with the observed degassing patterns of submarine basalts from progressively shallower depths along the Reykjanes Ridges.

THE CALCULATION AND USE OF CHEMICAL VAPOR DEPOSITION PHASE DIAGRAMS WITH APPLICATIONS TO THE Ti-B-Cl-H SYSTEM BETWEEN 1200 AND 800K, E. Randich and T. M. Gerlach, Sandia National Laboratories, Thin Solid Films, 75 (1981) 271-291.

A simple method for calculating multicomponent 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 1200 and 800 K. Examples of applications of the diagrams for yield optimization and experimental accessibility studies are presented and discussed. Experimental verification of phase field boundaries

at 1200 K, $H/Cl = 1$ and $H/Cl = 5$, confirms the calculated boundaries and indicates that equilibrium is nearly and rapidly approaches in this system under laboratory conditions.

D. Energy Extraction

TWO-DIMENSIONAL TEMPERATURE DISTRIBUTION SURROUNDING AN INJECTION WELL, J. C. Dunn, Sandia National Laboratories, Proceedings of AIAA 16th Thermophysics Conference, June 23-25, 1981, Palo Alto, California.

A two-dimensional analytical solution is obtained for the steady-state temperature distribution in a porous medium during injection of an incompressible fluid. Energy transfer by radial convection and by both radial and axial conduction are included. Temperatures in the porous medium can be expressed in terms of geometry and a non-dimensional Peclet number that includes the injection flow rate and properties of the formation and injected fluid. The solution can be applied to the injection of spent brine in geopressured or geothermal systems where temperature distribution near the injection well is needed in order to predict dissolution of suspended solids. Radial and axial temperature distributions are presented as a function of the Peclet number.

ENERGY EXTRACTION FROM MAGMA, J. C. Dunn, Sandia National Laboratories, Proceedings of 1981 IAVCEI Symposium on Arc Volcanism, Tokyo, Japan, August 28-September 9, 1981.

The objective of the DOE-funded Sandia Magma Energy Research Project is to investigate the scientific feasibility of extracting energy from shallow magma systems within the crust. Large amounts of thermal energy must exist in igneous-related systems in the upper 10 km of the crust. In the western United States alone, Smith and Shaw (1979) estimate that 10^{23} J (10^5 quads) of thermal energy is contained in evaluated young igneous-related systems within the 10 km depth. A crucial aspect of our investigation is determination of energy extraction rates that can be realized from a drillhole, for the energy extraction rates will probably determine the incentive for development of this major energy resource.

SUPERCONVECTING ZONES ABOVE SHALLOW HEAT SOURCES IN THE EARTH, J. C. Dunn, Sandia National Laboratories, Proceedings of 1981 IAVCEI Symposium on Arc Volcanism, pp. 80-81, Tokyo, Japan, August 28-September 9, 1981.

Two fluid phases (liquid and gas) can coexist in a porous medium only when the pore pressure is less than the fluid critical pressure. In the crust, when depth exceeds that corresponding to the critical pressure, a pure fluid can exist either as a liquid or as a gas, dependent on fluid temperature, and changes from one state to the other occur continuously without phase separation. However, significantly enhanced

fluid movement and energy transport can occur when fluid temperature and pressure are near their critical values. Such temperature and pressure conditions in the crust could be expected in geologically active regions of the world near plate boundaries.

CONVECTIVE HEAT EXTRACTION FROM MOLTEN MAGMA, H. C. Hardee, Sandia National Laboratories, Journal of Volcanology and Geothermal Research 10(1981) No. 1-3, p. 175.

The convective heat of molten magma in the upper 10 km of the continental crust represents a significant geothermal energy resource. Shallow basaltic magmas (< 10 km) near the liquidus (1250°C) are predicted to offer heat extraction rates in the range of $15\text{--}50\text{ kW/m}^2$ ($20\text{--}80\text{ MW/well}$). More accessible andesitic and wet rhyolitic magmas are predicted to offer heat extraction rates in the range of $5\text{--}25\text{ kW/m}^2$ ($8\text{--}40\text{ MW/well}$). Convective heat transfer correlations are used which include corrections for high Prandtl number fluids and cylindrical boundary layers. The calculations based on these correlations agree well with laboratory tests using molten basalt at superliquidus temperatures ($1450\text{--}1650^{\circ}\text{C}$). At liquidus and subliquidus temperatures an additional correction is developed for the thick solidified crust that forms on the heat exchanger. Non-Newtonian rheology is considered and shown to have a possible effect on the initiation of convection in the liquidus and subliquidus temperature range. In addition to heat extraction estimates, the analysis presented here is also relevant to convective heat loss to walls of magma bodies.

CONVECTIVE HEAT TRANSFER IN MAGMAS NEAR THE LIQUIDUS, H. C. Hardee and J. C. Dunn, Sandia National Laboratories, Journal of Volcanology and Geothermal Research Vol. 10, No. 1, pp 195-207 (1981).

Natural convection in magmas at subliquidus temperatures is analyzed using Bingham plastic and power-law rheology models. Heat flux measurements were obtained at liquidus and subliquidus temperatures for degassed basaltic lava at atmospheric pressure. These measurements of heat flux ranged from 6 to 40 kW/m^2 and were obtained using two different types of convective heat flux probes. The agreement between the two different instruments and the theoretical calculations is encouraging. A noticeable change in the trend of the convective heat flux data is observed in the vicinity of the liquidus temperature. The subliquidus convective heat flux rates (6 to 15 kW/m^2) are attractive for energy extraction applications.

E. Field Experiments

THE COOLING OF KILAUEA IKI LAVA LAKE, Richard G. Hills, Sandia National Laboratories, SAND81-0114.

In 1959 Kilauea Iki erupted leaving a 110 to 120 m lake of molten lava in its crater. The resulting lava lake has provided an unique opportunity to study the cooling dynamics of a molten body and its associated hydrothermal system. Field measurements taken at Kilauea Iki indicate that the hydrothermal system above the cooling magma body goes through several stages, some of which are well modeled analytically. Field measurements also indicate that during most of the solidification period of the lake, cooling from above is controlled by two-phase convection while conduction dominates the cooling of the lake from below. In this report, a summary of the field work related to the study of the cooling dynamics of Kilauea Iki is presented. Quantitative and qualitative cooling models for the lake are discussed.

THERMAL PROPERTY MEASUREMENTS IN A FRESH PUMICE FLOW AT ST. HELENS, H. C. Hardee, Sandia National Laboratories, Geophysical Research Letters (1981), Vol. 8, No. 3, pp 210-212.

A thermal penetrator that was air dropped into a freshly emplaced pumice flow at Mt. St. Helens yielded information on the in situ thermal properties of the pumice. The in situ conductivity-density-specific heat product at a depth of 60 cm was found to be $7.24 \times 10^{-5} \text{ cal}^2/\text{cm}^4\text{s-}^\circ\text{C}^2$ at an average pumice temperature of 200°C . Using this data, values for the average in situ thermal conductivity ($2.9 \times 10^{-4} \text{ cal/cm-s-}^\circ\text{C}$) and thermal diffusivity ($1.2 \times 10^{-3} \text{ cm}^2/\text{s}$) were estimated. These thermal properties are of use in studies of pumice cooling and in the interpretation of infrared remote sensing data.

PROBING THE MELT ZONE IN KILAUEA IKI LAVA LAKE, H. C. Hardee, J. C. Dunn, R. G. Hills, Sandia National Laboratories, R. W. Ward, University of Texas at Dallas, Geophysical Research Letters (1981), Vol. 8, No. 12, pp 1211-1214.

New drilling techniques were recently used to drill and core the melt zone of Kilauea Iki lava lake. Unique seismic transmission measurements were made through the melt zone yielding the first in situ seismic velocity data through a petrologically and thermally characterized melt zone. Periodic seismic sources were used to effectively penetrate the highly fractured hydrothermal zone of the lava lake crust. Thermal convection experiments in the melt zone resulted in the first controlled in situ measurements of the interaction of water with a basaltic melt zone. Transient energy rates of 900 kW and

steady rates of 85 kW were observed. These seismic and thermal measurements have important implications for the location of magma bodies in the crust and for the efficient extraction of energy from these bodies.

F. Project Reviews/Summaries

MAGMA ENERGY--A FEASIBLE ALTERNATIVE? John L. Colp, Sandia National Laboratories, International Associates of Volcanology and Chemistry of Earth's Interior, 1981 ARC Volcanism Symposium, August 28-September 9, 1981, Tokyo, Japan.

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 under way 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.

III. GENERAL GEOSCIENCE STUDIES

Introduction

In addition to the directed research in drilling and completions, instrumentation and magma energy, work support other local and national programs is also in progress. The geothermal technology based programs provide background for studies in the National Research Council's Continental Scientific Drilling Program, National Science Foundation's Ocean Drilling Program, Department of Defense's program on alternate energy resources and other similar programs. This section of the bibliography includes reports issued in these and other miscellaneous areas.

A. Continental Scientific Drilling Program

DRILLING, INSTRUMENTATION AND SAMPLING CONSIDERATIONS FOR GEOSCIENCE STUDIES OF MAGMA-HYDROTHERMAL REGIMES, R. K. Traeger, S. G. Varnado, A. F. Veneruso, V. L. Behr, A. Ortega, Sandia National Laboratories, SAND81-0800.

A deep drill hole into a magma-hydrothermal system would provide access to the third dimension needed to understand processes in the earth's crust and to resolve the ambiguities in existing models derived from two-dimensional, surface geoscience studies. Magma-hydrothermal systems are of interest for basic understanding of heat and mass transport in the earth's crust, for evaluation of geothermal energy resources, an understanding of mineral deposition processes and for assessment of such hazards as volcanic eruptions, earthquakes, and waste disposal.

The purpose of this paper is not to promote drilling a deep well, but to identify technological limitations, point out potential scientific-technology conflicts, provide an estimate of times and costs and to initiate interaction between the scientific and engineering community for an effective CSDP program. This paper reviews the drilling, diagnostic and sampling technologies needed to provide data from the third dimension for the scientific studies. Deep gas wells are frequently drilled to depths of 7-10 km at temperatures to 220°C in sedimentary formations. Geothermal wells are drilled to 3-5 km, 250-350°C in metamorphic or igneous formations. Holes have been drilled to a depth of 60 m into partially molten rock in lava lakes. However, the technology is not available to drill and perform measurements in formations at depths of 6-10 km at temperatures over 350°C as needed for studies of magma-hydrothermal systems. The major technological limitation is the ability to recover solid, liquid and gas samples at in situ conditions at temperatures exceeding 200°C. Deep drilling into hot formations and logging diagnostics using dewatered instruments appear feasible if the well is kept at low temperatures by circulating coolant. However, a cold well negates meaningful, important temperature and heat flow measurements. In addition, the wellbore may collapse when the equilibrium formation temperature is attained because of thermal stresses and the lack of a casing cement that retains strength at temperatures over 350°C.

CONTINENTAL SCIENTIFIC DRILLING PROGRAM: MAGMA-HYDROTHERMAL REGIMES, R. K. Traeger and H. C. Hardee, Sandia National Laboratories, Society of Petroleum Engineers of AIME 56th Annual Technical Conference, October 4-7, 1981, San Antonio, TX.

Deep drilling has been proposed to provide the third dimension of geoscience information on the structure, origin, dynamics,

and processes occurring in the continental crust. One thrust of the program is to describe the transport processes occurring in magma-hydrothermal regimes for understanding geothermal reservoir dynamics, ore deposition processes and potential for abiogenic methane. The third dimension will also provide data for resolving some conflicts in geological models as developed by surface geophysics.

Current plans are to drill to depths of 2-4 km, 300-400°C with extensive coring, logging, and other scientific studies. The hole would then be extended to 5-10 km, 400-1000°C for continued research. Potential sites for this hole have been identified and a preliminary ten-year program outlined.

This paper will summarize the program goals, review the site selection results and describe the proposed drilling, casing and logging program. Specific technological limitations will be discussed. The purposes of the paper are to describe the program to the drilling and logging community for critique and recommendations, and to initiate the needed scientific-engineering interactions.

SUPERCONVECTING GEOTHERMAL ZONES, J. C. Dunn, H. D. Hardee, Sandia National Laboratories, Journal of Volcanology of Geothermal Research (1981), Vol. 11, No2-4, pp 189-201.

Groundwater will circulate in a permeable medium by a process of natural convection if a sufficient temperature gradient exists. In the vicinity of the fluid critical point, the natural convective circulation increases dramatically. Laboratory data are presented which show that heat transfer rates in a permeable medium can increase by a factor of 70 in the vicinity of the critical point. The conditions for this type of superconvection are shown to be compatible with expected geologic conditions above magma bodies in the crust. This enhanced heat transfer process has potential application to energy extraction concepts and is shown to be capable of yielding heat extraction rates of 12 kW/m². A number of geophysical implications, such as shallow pooling of magma as sills, are briefly discussed.

B. Albuquerque Area Geothermal

GEOTHERMAL STUDIES AT KIRTLAND AIR FORCE BASE, ALBUQUERQUE, NEW MEXICO, SAND81-0852, Linda Riddle, Sandia National Laboratories, Bob Grant, Energy Resources Exploration, Inc.

Due to an effort by government installations to discontinue use of natural gas, alternative energy sources are being investigated at Kirtland Air Force Base, Albuquerque, New Mexico. New Mexico has geologic characteristics favorable for geothermal energy utilization. Local heat flow and geochemical studies indicate a normal subsurface temperature regime. The alluvial deposits, however, extend to great depths where hot fluids, heated by the normal geothermal gradient, could be encountered.

GEOTHERMAL RESOURCE VERIFICATION FOR AIR FORCE BASES, SAND81-7123, Philip R. Grant, Jr., Energy Resources Exploration, Inc., under contract to Sandia National Laboratories.

Geothermal energy offers a potential alternative to oil and gas for supplying the stationary energy requirements of military installations. However, because of the past dominance of oil and gas, procedures for estimating geothermal energy potential have not been well defined nor well tested.

This report summarizes the various types of geothermal energy, reviews some legal uncertainties of the resource and then describes a methodology to evaluate geothermal resources for applications to U.S. Air Force bases. Estimates suggest that exploration costs will be \$50-300,000, which, if favorable, would lead to drilling a \$500,000 exploration well. Successful identification and development of a geothermal resource could provide all base, fixed system needs with an inexpensive, renewable energy source.

C. Miscellaneous

GEOHERMAL TECHNOLOGY PUBLICATIONS AND RELATED REPORTS: A BIBLIOGRAPHY, January 1977 to December 1980, SAND81-0662, Sandra R. Hudson, Editor, Sandia National Laboratories.

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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4743 H. C. Hardee (10)
4746 B. Granoff
4747 P. J. Hommert
4750 V. L. Dugan
4752 H. M. Dodd
4753 D. A. Northrop
4755 B. W. Marshall
4756 D. Engi
5500 O. E. Jones
5541 W. C. Luth
8214 M. A. Pound
3141 L. J. Erickson (5)
3151 W. L. Garner (3)