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**GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY
DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT**

JANUARY 1981-MARCH 1981

JAMES R. KELSEY, EDITOR

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of
Energy under Contract DE-AC04-76BP00789.

JUNE 1981

Sandia National Laboratories

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Printed in the United States of America
Available from:
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$9.00; Microfiche \$3.00

SAND81-1020
Unlimited Release
Printed June 1981

Category UC-66c

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
QUARTERLY PROGRESS REPORT

January 1981-March 1981

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Editor
Geothermal Technology Development Division 4741
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Albuquerque, NM 87185

ABSTRACT

This report describes the progress, status, and results of ongoing Research and Development (R&D) 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 program emphasizes the development of geothermal drilling hardware, drilling fluids, completion technology, and lost circulation control methods as they apply to advanced drilling systems.

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CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION	13
2	HIGHLIGHTS	15
3	MANAGEMENT	19
4	DRILLING HARDWARE	21
	4.1 Continuous Chain Bit--Sandia National Laboratories	25
	4.2 Geothermal Polycrystalline Diamond Compact Drill-Bit Development--GE (CRD)	31
	4.3 Wear Mechanisms of Polycrystalline Diamond Compacts--GE (CRD)	37
	4.4 Wellbore Inertial Navigation System-- Sandia National Laboratories	63
5	DRILLING FLUIDS	65
	5.1 Aqueous Foam Drilling Fluids for Geothermal Applications--Sandia National Laboratories	67
	5.2 Nitrogen/Drill Pipe Corrosion Test--Sandia National Laboratories	81
	5.3 High-Temperature/High-Pressure Drilling Mud Research Instrumentation--NL Baroid	83
	5.4 Drilling Mud Chemistry--Texas Tech University	87
6	COMPLETION TECHNOLOGY	99
	6.1 High-Temperature Perforator--Sandia National Laboratories	101
	6.2 Cavitation Descaling Technique for Downhole Geothermal Well Cleaning--Daedalean Associates, Inc.	105
	6.3 Drilling Fluid/Formation Interactions-- Terra Tek, Inc.	107
	6.4 Completion Equipment Study--Foster-Miller Associates, Inc.	111
	6.5 Completion Life Cycle Cost Model-- The BDM Corporation	117

CONTENTS (Continued)

<u>Section</u>		<u>Page</u>
7	LOST CIRCULATION CONTROL METHODS	121
7.1	Lost Circulation/Cementing Test Facility-- Sandia National Laboratories	123
7.2	Lost Circulation Material Screening Apparatus-- Sandia National Laboratories	125
7.3	Evaluation of Techniques and Hardware for Drilling Through Lost Circulation Zones-- Maurer Engineering, Inc.	129
8	SUPPORTING TECHNOLOGY	133
8.1	Bit Hydraulics Studies--Sandia National Laboratories	137
8.2	Drill Stem Corrosion--Sandia National Laboratories	145
8.3	Rock Mechanics for Polycrystalline Diamond Com- pact Cutters--Sandia National Laboratories	155
8.4	Modification and Extension of Testing Capa- bilities--Drilling Research Laboratory, Inc.	157
8.5	Development of an Advanced Wellbore Thermal Code--Enertech Engineering and Research Co.	161
8.6	Casing Stress Analysis--Sandia National Laboratories	201
9	ADVANCED DRILLING SYSTEMS	205
9.1	Characterization of High-Pressure Jet Drilling Systems--Foster-Miller Associates, Inc.	209
9.2	Improvement of Downhole Drilling-Motor Bearings and Seals--Terra Tek, Inc.	213
9.3	Design and Fabrication Support of Bearing/Seal Research--Maurer Engineering, Inc.	219
9.4	Percussion Drilling Hammers and Bits-- Sandia National Laboratories	221
9.5	Development of Improved Cavijet® Nozzles-- Hydronautics, Inc.	223
9.6	Flexible Drilling Pipe--L'Garde, Inc.	229
9.7	High-Pressure Fluid Delivery Systems--Flow Industries, Inc.	231
9.8	High-Speed Polycrystalline Diamond Compact Drill Bits--Sandia National Laboratories	233
	APPENDIX A--Publications and Presentations	249

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
4-1	Penetration Rates of Link Sets Tested at DRL in Sierra White Granite at 193 MPa (28 ksi)	27
4-2	Thermocouple Locations for a Sharp Stratapax™ Drill Blank Cutter and Stud	39
4-3	Thermocouple Locations for a Dull Stratapax™ Drill Blank Cutter and Stud; Wearback = 0.047 in.; Wear Flat Area = 0.030 in.	40
4-4	Temperatures Developed in Stratapax™ Drill Blank Cutter No. 8 Cutting Tennessee Marble	41
4-5	Cross Section through Rock Showing Standing Circular Ridge Prepared for Cutting Temperature Experiments	42
4-6	Stratapax™ Drill Blank Cutter/Rock Configuration Used for Cutting-Temperature Measurements and Calculation of Ground Wear Flat Area for Cutter No. 8	43
4-7	Measurements Made to Calculate Wear Volume and Wear Scar Areas for Stratapax™ Drill Blank Cutters	51
4-8	Wear Volume as a Function of Distance Cut for Cutters Nos. W-1 through W-6, Cutting Nugget Sandstone with a Water-Base Coolant of 40:1 Water-Soluble Oil at a Flow Rate of 0.024 m ³ /min (6.3 gal/min)	58
4-9	Wear Volume as a Function of Distance Cut for Cutters Nos. W-7 through W-12 Cutting Nugget Sandstone in Air	60
5-1	Effective Thermal Conductivity versus Liquid Volume Fraction	70
5-2	Sandia National Laboratories Thermal Conductivity Probe	71
5-3	Representative Temperature Probe Response versus Log Time	72
5-4	Representative Temperature Probe Response versus Log Time	73
5-5	Representative Temperature Probe Response versus Log Time	74
5-6	Preliminary Thermal Conductivity Data	76
5-7	Thermal Conductivity Probe, Model CS-48, Custom Scientific Instruments	78
5-8	Thermal Conductivity Apparatus	79
5-9	Clays in the Pores of Test Core 2-64A	89
5-10	A Higher Magnification View of the Predominant Clays in Test Core 2-64	90
5-11	Typical Hairy Illites Growing from Flaky Illite/Smectite Mixed Layers in the Virgin Core, Section C	91

ILLUSTRATIONS (Continued)

Figure		Page
5-12	Rheograms of Pure Sepiolite Muds as Measured by the Fann 50C Viscometer	96
5-13	Rheograms of Pure Sepiolite Muds as Measured by the Fann 50C Viscometer	97
5-14	Rheograms of Sepiolite/MgCl ₂ Muds Nos. 4, 5, and 6, Which Were Autoclaved at 204°, 260°, and 316°C (400°, 500°, and 600°F), Respectively	98
7-1	Lost Circulation Test Cell	126
7-2	Geothermal Lost Circulation Test Apparatus	127
8-1	Local Convective Heat Transfer Coefficient Measurements for a Cylinder in Crossflow	138
8-2	Mean Convective Heat Transfer Coefficient for a Cylinder in Crossflow	139
8-3	Local Convective Heat Transfer Coefficient Measurements for a PDC Stud in Crossflow	141
8-4	Typical Flow Pattern in Bit Blank Test	142
8-5	Typical Flow Pattern in Bit Blank Test	142
8-6	Sandia 16.5-cm (6.5-in.) PDC Stud Bit	143
8-7	Tensile Test Data for Intermediate Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.75Si-0.1V-0.1C with Longitudinal Orientation	146
8-8	Tensile Test Data for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C with Longitudinal Orientation	148
8-9	Fatigue Test for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in Dry Air ($\Delta k = K_{\max.} - K_{\min.}$, $0.1 K_{\max.} = K_{\min.}$)	149
8-10	Fatigue Test for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in NACE Brine ($\Delta k = K_{\max.} - K_{\min.}$, $0.1 K_{\max.} = K_{\min.}$)	150
8-11	Fatigue Test for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in H ₂ S-Saturated NACE Brine ($\Delta k = K_{\max.} - K_{\min.}$, $0.1 K_{\max.} = K_{\min.}$)	151
8-12	Fatigue Test Results for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in Various Environments ($\Delta k = K_{\max.} - K_{\min.}$, $0.1 K_{\max.} = K_{\min.}$)	152

ILLUSTRATIONS (Continued)

<u>Figure</u>		<u>Page</u>
8-13	Fatigue Test Results for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C and Grade E Materials in H ₂ S-Saturated Brine ($\Delta K = K_{\text{max.}} - K_{\text{min.}}$, $0.1 K_{\text{max.}} = K_{\text{min.}}$)	153
8-14	Pressure Results from the Solids Transport Model Test Using a Bottomhole Pressure of 1,101 kPa (147 psi)	163
8-15	Velocity Results from the Solids Transport Model Test Using a Bottomhole Pressure of 1,101 kPa (147 psi)	164
8-16	Density Results from the Solids Transport Model Test Using a Bottomhole Pressure of 1,101 kPa (147 psi)	165
8-17	Volume Fraction Results from the Solids Transport Model Test Using a Bottomhole Pressure of 1,101 kPa (147 psi)	166
8-18	Pressure Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (73.5 psi)	167
8-19	Density Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (73.5 psi)	168
8-20	Volume Fraction Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (73.5 psi)	169
8-21	Velocity Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (73.5 psi)	170
8-22	Exit Gas Pressure Sensitivity to Element Length	172
8-23	Solids Volume Fraction Sensitivity to Element Length	173
8-24	Solids Transport Velocities Based on the Solids Transport Model by R. Angel	175
8-25	Gas Pressure Results Based on the Solids Transport Model	176
8-26	Gas Densities Based on the Solids Transport Model by R. Angel	177
8-27	Volume Fraction Results Based on the Solids Transport Model by R. Angel	178
8-28	Solids Transport Velocities Recalculated Using a More Realistic Particle Size	179
8-29	Gas Densities Recalculated Using a More Realistic Particle Size	180
8-30	Volume Fraction Results Recalculated Using a More Realistic Particle Size	181
8-31	Gas Pressures Recalculated Using a More Realistic Particle Size	182

ILLUSTRATIONS (Continued)

<u>Figure</u>		<u>Page</u>
8-32	Saturation Liquid Density Correlations of the Drilling Mist Model Compared to Tabulated Values	183
8-33	Saturation Vapor Density Correlations of the Drilling Mist Model Compared to Tabulated Values	184
8-34	Saturation Vapor Pressure Correlations of the Drilling Mist Model Compared to Tabulated Values	185
8-35	Liquid and Vapor Enthalpy Correlations of the Drilling Mist Model Compared to Tabulated Values	186
8-36	Summary of Mixture Relations for a One-Dimensional, Multiphase Flow Model	188
8-37	Solids Transport Model Equations Simplified from the Equations in Figure 8-36	190
8-38	Relations for a Two-Phase Model with Phase Change	192
8-39	Mass Flow Rate Densities of a Two-Phase Flow, Water-Steam Mixture	194
8-40	Flowing Steam Temperature of a Two-Phase Flow, Water-Steam Mixture	195
8-41	Flowing Steam Pressures of a Two-Phase Flow, Water-Steam Mixture	196
8-42	Flowing Steam Velocity of a Two-Phase Flow, Water-Steam Mixture	197
8-43	Casing Configuration Used in the Analysis	201
8-44	Transient Temperature Profiles Computed by COYOTE	203
8-45	Boundary Conditions for Structural Analysis	204
9-1	HTCR SF-Design Seal Cross Section	214
9-2	Canted Seal Cross Section	214
9-3	Variseal® Cross Section	215
9-4	PDC Drill Bits, 17.1 cm (6-3/4 in.) in Diameter, Supplied by Bit Manufacturers	234
9-5	Sandia National Laboratories' 16.5-cm (6-1/2-in.) PDC Bit	234
9-6	Christensen 17.1-cm (6-3/4-in.) PDC Drill Bit after Drilling 0.9 to 1.2 meters (3 to 4 feet) in Texas Pink Granite	235
9-7	Performance Characteristics of Bits Nos. 1, 3, 5, and 8 at 100 rpm in Nugget Sandstone	237
9-8	Performance Characteristics of Bits Nos. 1, 3, 5, and 8 at 500 rpm in Nugget Sandstone	238

ILLUSTRATIONS (Continued)

<u>Figure</u>		<u>Page</u>
9-9	Torque Characteristics of Bits Nos. 1, 3, 5, and 8 at 500 rpm in Nugget Sandstone	239
9-10	Performance Characteristics of Bits Nos. 8 and 9 at 100 rpm in Crab Orchard Sandstone	241
9-11	Performance Characteristics of Bits Nos. 1, 3, 5, 8, and 9 at 500 rpm in Crab Orchard Sandstone	242
9-12	Torque Characteristics of Bits Nos. 3, 5, 8, and 9 at 500 rpm in Crab Orchard Sandstone	243
9-13	Security Bit No. 6 Test Results in Sierra White Granite at 500 and 100 rpm	245
9-14	Performance Characteristics of Sandia Bit No. 9 at 100 rpm in Sierra White Granite	246

TABLES

<u>Table</u>		
4-1	Comparison of the Approximate Wear Flat Area and the Exact Wear Flat Area as a Function of Wearback	45
4-2	Results of Plunge Cut Tests with Stratapax™ Drill Blank Cutter No. 8 on Tennessee Marble, Using 40:1 Water-Soluble Oil Coolant at a 0.24-m ³ /min (6.3-gal/min) Flow Rate Directed Against the Circular Face of the Cutter	47
4-3	Locations of the Six 5.08-cm (2.0-in.) Wide Concentric Circular Bands Used for Stratapax™ Drill Blank Wear Tests Cutting Nugget Sandstone and the Cutting Speeds at 51.24 rpm	49
4-4	Wear Test Conditions for Stratapax™ Drill Blank Cutters Nos. W-1 through W-6 Cutting Nugget Sandstone with 40:1 Water-Soluble Oil Coolant at a 0.024-m ³ /min (6.3-gal/min) Flow Rate	54
4-5	Wear Test Conditions for Stratapax™ Drill Blank Cutters Nos. W-7 through W-12 Cutting Nugget Sandstone Dry (in Air)	54
4-6	Summary of Experimental Wear Test Results for Stratapax™ Drill Blank Cutters Nos. W-1 through W-6	55
4-7	Summary of Experimental Wear Test Results for Stratapax™ Drill Blank Cutters Nos. W-7 through W-12	56

TABLES (Continued)

<u>Table</u>		<u>Page</u>
4-8	Data Column Headings for Tables 4-6 and 4-7	57
5-1	Interplanar Spacing Measurements, d-Values, Obtained by the X-Ray Diffraction of the Drilling Fluids after Hydrothermal Treatment at 371°C (700°F) and at 427°C (800°F)	92
5-2	Rheological Data on Sepiolite Mud as Obtained from the Measurements with the FANN 35A Viscometer	95
7-1	Evaluation Summary	131
9-1	Seal Test Conditions	215
9-2	Key Design Features	235
9-3	Experimental PDC Drill Bits	236
9-4	Wear Test Results	247

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT

January-March 1981

1. INTRODUCTION

The high cost of drilling and completing geothermal wells is an impediment to the timely development of geothermal resources in the U.S. The Division of Geothermal Energy (DGE) of the Department of Energy (DOE) has initiated a development program aimed at reducing well costs through improvements in the technology used to drill and complete geothermal wells. Sandia National Laboratories (SNL) has been selected to manage this program for DOE/DGE. Based on analyses of existing well problems, research goals have been set for the program.

To meet these goals, technology development in a wide range of areas is required. The near-term goal will be approached by improvements in conventional, rotary drilling technology. The long-term goal will require the development of an advanced drilling and completion system. Currently, the program is completing activities which are near commercialization and increasing emphasis on advanced system development.

The program is structured into six sub-elements: Drilling Hardware, Drilling Fluids, Completion Technology, Lost Circulation Control Methods, Advanced Drilling Systems, and Supporting Technology. Technology development in each of these areas is conducted through contracts with private industries and universities. In addition, many projects are conducted internally by Sandia.

This report describes the program, status, and results of ongoing R&D within the program for the quarter January-March 1981.

2. HIGHLIGHTS

- Program Reorientation and Reporting -- The Geothermal Drilling and Completion Technology Development Program is being restructured in order to be compatible with the large-scale reduction in resources scheduled for FY 1982. Future program work will emphasize research and development activities with less effort aimed at commercialization of technology. In consonance with the cut back in resources, future quarterly progress reports will present only brief overviews of project activities. The annual report of fiscal year progress will contain summaries of significant data, achievements, and findings, as appropriate, from each project in the program. Comprehensive details on each project will be available in the final report that will be published separately for each project. As part of the overall reorganization of geothermal technology research, reports on the work in logging instrumentation and high-temperature instrumentation will be included in this program's quarterly and annual progress reports.

- Drilling Fluid/Formation Interactions -- This project was completed during this reporting period. The final report is being prepared and will be published separately.

- Lost Circulation Material Screening Apparatus -- Reporting on this project was initiated this quarter. Under the project, an economical, simple screening apparatus will be fabricated to permit the testing of a large matrix of materials in a short period of time. The most promising materials will then be subjected to a comprehensive evaluation in the Lost Circulation/Completion Test Facility.

- Evaluation of Techniques and Hardware for Drilling through Lost Circulation Zones -- This project was completed during this reporting period. A final report is being prepared and will be published separately. A summary of the evaluation results and preliminary conclusions are contained in Section 7.3.

- High-Speed Polycrystalline Diamond Compact (PDC) Drill Bits -- Reporting on this project was initiated this quarter. Six different PDC drill bit designs will be evaluated at high speeds in three different types of rocks. The results of the initial laboratory tests are reported in Section 9.8.

- Casing Stress Analysis -- Reporting on this project was initiated this quarter. Existing techniques for thermal stress analysis are being applied to generic geothermal casing problems to identify and understand the stresses developed in geothermal well casing and to develop casing design criteria. The initial work is described in Section 8.6.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

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 - - - - - RESCHEDULED ● STARTED ▼ COMPLETED

3. MANAGEMENT

Advisory Panel

The semiannual meeting of the Geothermal Drilling and Completion Advisory panel was held on 19-20 January 1981 in Albuquerque, New Mexico. The minutes of the meeting have been published separately.

International Conference

An International Conference on Geothermal Drilling and Completion Technology, which was cosponsored by the U.S. Department of Energy, the Comisión Federal de Electricidad de México, and Sandia National Laboratories, was held at the Four Seasons Hotel, Albuquerque, New Mexico, 21-23 January 1981. Over 300 persons attended the conference, including representatives from 13 foreign countries. The proceedings of the conference have been published separately.

Systems Analysis

A paper entitled "Geothermal Well Costs and Their Sensitivities to Changes in Drilling and Completion Operations" was presented at the International Conference on Geothermal Drilling and Completion Technology. The paper summarized a study on geothermal well costs and is included in the proceedings of the conference that have been published separately.

Two presentations were made at the January 1981 meeting of the Geothermal Drilling and Completion Technology Advisory Panel. One presentation evaluated the progress of the Geothermal Drilling and Completion Technology Development Program toward meeting the near-term and long-term program goals; both types of goals are considered attainable provided that planned funding levels are maintained. The second presentation outlined the results of an erosion drilling study conducted by Foster-Miller Associates. The technology gathered in the study provides excellent background data and appears useful for geothermal applications. A final report on the study is nearing completion.

Trouble-free representative well models have been completed for major geothermal resource areas and are being used to evaluate the applicability and impact of new bit and drilling technologies. The models are also being used to provide inputs to the development of the completions life cycle cost model and to the study of balanced pressure drilling.

Current effort is directed towards compiling data on problems encountered at the principal geothermal resource areas during drilling, completion, and production. The effects and probabilities of problems will be included in the representative well models to more realistically reflect total well costs. This addition will aid in the comparative evaluation of new technologies.

4. DRILLING HARDWARE

In order to reduce well drilling costs, improved drilling hardware that has a longer life and that drills at an increased rate of penetration is required. The approach to achieving the needed improvements includes the development and demonstration of a new drill bit concept, the improvement of existing hardware systems and subsystems, and research into new materials and rock-fracture/cutter wear mechanisms. Projects are presently under way to design and demonstrate drag bits using polycrystalline diamond compact (PDC) cutters; design, fabricate, and test a prototype, downhole, replaceable drill bit; and investigate rock-fracture/cutter wear mechanisms and the effects of drilling fluids on the required cutting force, wear mechanisms, and wear rates of PDC cutters. The status and progress of these activities are described within this section.

A completed project on unsealed geothermal drill bit development has identified new materials for use in critical areas of conventional roller-cone bits. These materials demonstrated improved hardness and toughness at high temperatures and extended the life of the bits in hard, geothermal formations. Six experimental bits were evaluated in a geothermal well at The Geysers along with seven conventional bits. The improvements in materials allowed the experimental bits to drill 30% longer before incurring the same gage wear as the conventional bits, and 70% more hole was drilled to gage than with a conventional control bit. Bearing wear was also reduced significantly. By decreasing the number of bits needed to drill a well and reducing rig time costs, bits using the new materials would save 2% to 4% of the total cost of wells drilled in The Geysers.

Experiments with high-temperature seal designs, materials, and lubricants for sealed-bearing bits have identified promising seal/lubricant systems for geothermal use. An oil, designated PLX-014, has demonstrated a load-bearing capability at 316°C (600°F) roughly twice that of the standard rock-bit lubricant at room temperature. A grease version of PLX-014 oil tested at 317°C (603°F), while showing, as expected, an average load-carrying capability somewhat less than the oil, still exceeded standard lubricant load capabilities by 50%. Both the oil and grease version of PLX-014 proved compatible with elastomeric seals fabricated from Viton and Teflon-coated Viton materials. Seal lives in the 100-hour range were demonstrated in seal tests at a temperature of 150°C (302°F) following pretest soaking of the seals at a temperature of 250°C (482°F). A test of a spring-loaded face seal with a Viton side-seal system at 200°C (392°F) ran for 76 hours with little leakage observed.

A prototype of the continuous chain drill concept, in which the cutting surfaces can be replaced without removing the bit from the hole, was successfully field tested in drilling granite at the Nevada Test Site (NTS)

in June 1979. The chain bit drilled a total of 76 meters (250 feet) with six cutting surfaces, and the chain was successfully cycled approximately 85 times downhole. The average drilling results for the six chain link sets were (1) footage drilled, 12.7 meters (41.6 feet); (2) weight on bit, 28 kN (6,400 pounds); and (3) rate of penetration, 1.2 m/h (4.0 ft/h). A second field test was conducted in September 1979, at which time internal hydraulic leakage occurred. This problem was corrected, and a third field test at NTS was completed in June 1980. No problems were encountered in cycling the chain downhole; however, as had occurred in the second field test, a rapid wearing of the chain link cutting surfaces occurred in the third field test, and the bit wore out quickly in the hard granite formation. The chain link seals were suspected of being the cause of the rapid wear and were studied this quarter. Also, the use of investment castings to make chain link bases and matrix pads is being investigated.

Full-scale drag bits modified to use PDC cutters have been evaluated in field tests. Both the Christensen (C-1) hard-matrix and the Smith (S-1, modified), steel-bodied, PDC bits were tested in October 1979 at a location in the Baca Field, New Mexico. Testing was in andesite, the basement formation for the geothermal wells being drilled by the Union Geothermal Company of New Mexico. The tests were run at depths of approximately 1,676 to 1,707 meters (5,500 to 5,600 feet). The C-1, hard-matrix bit drilled successfully with penetration rates up to 0.007 m/s (85 ft/h) at bit weights up to 88,964 newtons (20,000 pounds) and rotary speeds as high as 70 rpm. Cutter wear was not excessive, and the bit was still usable after the test. On the average, a 50% increase in penetration rate over that of a conventional bit was obtained. The S-1, modified, steel-bodied bit was found to be so aggressive in drilling this formation that bit weights greater than 44,482 newtons (10,000 pounds) could not be used. Instantaneous penetration rates as high as 0.014 m/s (170 ft/h) were obtained at a rotary speed of 60 rpm. Because these tests were limited to approximately 15.2 meters (50 feet) each, bit lifetime could not be established. Additional development and testing are planned to quantify and maximize bit lifetime and to optimize the bit design.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ——— ACTIVITY PERIOD ○ PLANNED START ▼ PLANNED COMPLETION
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4.1 Continuous Chain Bit

Sandia National Laboratories
Technical Consultant: B. Caskey (505) 844-8835

Project Objective

The objectives of this project are to design, fabricate, and test a prototype downhole replaceable drill bit and to obtain industrial participation in the development of the hardware.

Project Status

A Prototype II, Mod 2, continuous chain drill bit field test, field test I, was conducted at the Nevada Test Site (NTS) during the period 5-20 June 1979. A follow-up field test at NTS, field test II, was initiated in mid-September 1979. Unexpectedly rapid wear of the chain link cutting surfaces was experienced, and the tests were terminated after the determination was made that field repair of the drills could not be accomplished. A post-test analysis of the Mod 3 chain drills revealed that the mud flow channel in both bit bodies had ruptured. The failure is believed to have occurred during predrilling, surface, cycling tests.

The redesigning and fabrication of two Mod 4 chain drills were completed, and a third field test, field test III, was conducted in June 1980. As occurred in field test II, a rapid wearing of the chain link cutting surfaces also occurred in field test III. The chain link seals were suspected of being the cause of the rapid wear and were studied during laboratory testing this reporting period. A parallel effort to develop an all-PDC chain link is continuing. The use of investment castings to make chain link bases and matrix pads is being investigated.

The project program has been revised, reducing the research effort to comply with budgetary restraints. The hydraulics evaluation of the second-generation bit has been deleted along with industrial solicitation and industrial participation. The work on PDC chain links will be completed during the next quarterly reporting period. A final report summarizing the continuous chain bit drilling research program will be completed by the end of FY81.

Quarterly Progress

Drilling Performance Investigation -- Two new link sets were modified and a chain drill bit refurbished for testing at Drilling Research Laboratories (DRL), Salt Lake City. This work was a follow-up activity to the in-depth review of the three NTS field tests.

Tungsten carbide inserts in the fluid passages of two link sets were replaced with stainless steel inserts that had rubber adiprene seals molded

in place for each link. Link set No. 30 was prepared for the purpose of comparing its drilling capability to that of link set No. 10, which was successfully tested previously. Both of these link sets were fabricated to the same specifications.

The second link set, No. 26, was prepared primarily to determine what benefits can be attained by controlling the position of the diamond cutting pattern more closely. Special locating pins were placed in the chain link bases to position each link in the center of the drilling head slot with only slight movement allowed by a 0.0254 to 0.0508 mm (0.001 to 0.002 in.) clearance.

The two link sets were tested at DRL during the week of 23-27 February 1981. Link set No. 30 was life tested after spudding-in holes in Sierra white granite were shaped to the chain bit contour. The penetration rate versus depth drilled in this test is shown in Figure 4-1, and the data are compared with the performances of link set No. 10, which was tested in April 1979, and of link set No. 28, which was tested in August 1980. It was anticipated that link set No. 30 would perform about the same as link set No. 10. However, link set No. 30 drilled somewhat better than link set No. 28 but was significantly substandard to link set No. 10. The first examination of link set No. 30 after it had drilled 127 cm (50 in.) revealed that some diamonds on the trailing edge of links 1, 2, 4, and 5 were worn almost flush with the chain link matrix surface. Link set No. 10 showed no significant diamond wear until after drilling over 508 cm (200 in.). The rubber seals provided improved hydraulics, which was indicated by fluid erosion on the matrix surface. However, the rubber seals did not significantly improve bit life, as indicated by a comparison with the performance of link set No. 28.

The second set of chain links, link set No. 26, was installed and tested. After drilling 0.6 meter (2 feet), the chain links were inspected. The use of locating pins to center the links resulted in a significant change in the location of the diamond wear pattern. Also, the number of worn diamonds after 0.6 meter (2 feet) of drilling indicated that the drilling life would not be exceptional. The diamond wear pattern was predominantly on the leading edge of the chain link pads instead of on the trailing edge as was observed on link set No. 30. After 1.83 meters (6 feet) was drilled, it was discovered that the chain had been positioned on the drill bit incorrectly through operator error. Consequently, the drilling life test data for link set No. 26 are inconclusive.

Based on the tests described above, the following conclusions were drawn:

1. The poor drilling performance experienced in field tests II and III was not caused primarily because rubber seals were replaced with tungsten carbide inserts, as previously thought. However, the rubber seals are believed to be helpful for low-temperature drilling applications, and they will reduce the water loss between the base link and the bit head.
2. The chain link diamond wear pattern is affected by the position of the chain in the bit head slot. Closer positional control should provide more uniform wear.

Figure 4-1. Penetration Rates of Link Sets Tested at DRL in Sierra White Granite at 193 MPa (28 ksi)

3. The precise cause of the reduced drilling capability encountered in field tests II and III has yet to be determined.

Investigation is now being directed toward the final potential cause of the reduced drilling capability. This cause is diamond quality variation. Diamond type, shape, set, and quality parameters are unknown factors; these data are normally protected as company proprietary information. This project has been conducted under the assumption that premium diamonds were used in the manufacture of the chain drill components. However, diamonds are purchased on the world market and come from several geographical locations. Hence, it is reasonable to assume that diamond quality is a variable associated with such a commodity market. Sandia does not have the means to determine diamond quality other than by after-the-fact review of drilling results.

Christensen, Inc., the supplier of the chain links, is being requested to review its manufacturing records to determine if different types and/or sources of diamonds were used in the fabrication of chain links that drilled successfully versus those links whose drilling performance was unsatisfactory. Tests and visual inspections have been initiated at Sandia. Some differences in diamonds have been observed, but the manner in which these differences affect drilling capability remains unknown and must be determined.

Investment Casting Evaluation -- The use of the investment casting, lost wax process for making chain link bases in lieu of machined parts has been evaluated by the use of destructive testing techniques. The purpose of these tests was to compare the strength of the cast parts made from 17-4 PH stainless steel with the strength of the machined parts made from 9-4-20 alloy steel.

The first series of tests simulated a possible mode of failure in which the hooks in the chain bit body that are used to cycle the chain would shear off the engagement tabs on the base link. The test results follow:

Test	Failure Force		Material	Shear Stress	
	kg	(lb)		MPa	(psi)
1	4,853	(10,700)	17-4 PH	576.4	(83,594)
2	4,944	(10,900)	17-4 PH	581.8	(84,375)
5	5,171	(11,400)	9-4-20	614.1	(89,063)

A comparison of the average ultimate shear stress of tests 1 and 2 to test 5 indicates a difference of 5.7%.

The second series of tests was made on link bases that had a milled notch where the links engage a ratchet pawl or piston pawl. A cast 17-4 PH link base yielded under a tensile load of 5,466 kg (12,050 lb), or at a tensile stress of 1,034 MPa (150,000 psi). Based on the Von Mises theory, the stress value for shear using a yield stress of 1,034 MPa (150,000 psi)

is $\sigma_s = 0.577 \times 1,034$ MPa (150,000 psi). This value, 596.7 MPa (86,550 psi), agrees closely with the shear stresses experienced in Tests 1 and 2.

The third test series was conducted by pulling two or more link bases joined with connecting pins. These link bases did not have a milled notch or tabs for hooks. A comparison of 9-4-20 alloy steel and 17-4 PH stainless steel could not be made because the hardened steel pins joining the link bases failed first at loads in the 6,350-kg (14,000-lb) range.

These series of tests have verified that investment cast links made from 17-4 PH stainless steel have adequate strength when compared to the 9-4-20 alloy steel. The use of investment casting for fabricating production quantities of links should result in a significant cost reduction.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>PDC BIT DEVELOPMENT:</u> <u>GENERAL ELECTRIC</u> FIELD TESTING DESIGN MODIFICATION PERFORMANCE AND ECONOMIC ANALYSIS CONTRACTING	<div> <p>EXTENSION</p> <p>COMPLETED</p> <p>EXTENSION</p> <p>EXTENSION</p> </div>												

LEGEND: ——— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.2 Geothermal Polycrystalline Diamond Compact Drill-Bit Development

Contractor: General Electric Company, Corporate
Research and Development (GE/CRD)
Principal Investigator: L. E. Hibbs, Jr. (518) 385-8330
Contract Period: 30 June 1976 to 31 May 1981
Contract Number: DE-AC04-76ET27142
Technical Consultant: E. Hoover (505) 844-7315

Project Objective

The overall objective of this project is to develop and demonstrate the performance of a new type of drill-bit design that will provide increased penetration rates and/or longer bit life with high-pressure, sintered polycrystalline diamond compacts (PDCs) for the cutting edges. The scope of this contract includes instrumented rock-cutting experiments, diamond compact wear and failure mode analysis, rock removal modeling studies, bit design and construction, full-scale laboratory testing, and field testing.

Project Status

From experiments at atmospheric conditions on the cutting of rock with individual PDC cutters, a capability was established for the performance of full-scale bits. This capability was demonstrated with the laboratory testing of full-scale bits. Single-cutter tests were run at simulated downhole conditions, and the data were analyzed. Because of the catastrophic failure that occurred during the November 1978 field test, the S-1, modified, bit, was redesigned and fabricated. Both the S-1, modified, bit and the C-1, cast, hard-matrix bit were field tested in the Baca field, New Mexico, in October 1979. The S-1 bit demonstrated a penetration rate several times greater than typical rates for rock bits in similar formations.

Two S-2A bits were designed and fabricated for testing in the Baca field using aerated water as the drilling fluid. Subsequent testing in the laboratory and at the Baca location revealed a fabrication error in the S-2A bits.

Two S-2B bits were designed and fabricated for testing in The Geysers, California, using air as the drilling fluid. One of the S-2B bits was laboratory tested with good results; however, when tested at The Geysers, the other S-2B bit experienced excessive wear. The investigation of the cause of this wear was concluded this quarter. The study determined that the diamond compact cutters underwent localized thermal degradation caused by insufficient cooling during air drilling in a hot geothermal environment. Studies are continuing on the S-2B bit that was not tested at the Geysers.

Quarterly Progress

As previously reported, the S-2B stud-type Stratapax™* bit, Smith Tool bit designation SPX-015, lost 15 diamond compact cutters when tested at The Geysers, California. The condition of the bit after the field test suggested that the wear was not due to the fracturing of the cemented tungsten carbide studs, which had been observed in another instance, but possibly to premature Stratapax™ drill blank detachment followed by the grinding away of the studs in the very abrasive, hot environment. Therefore, an investigation to determine the principal failure modes was initiated. This investigation has included (1) an examination of the wear mechanism of selected diamond compact cutters still remaining on the bit and of the condition of the braze bond for these cutters and (2) an ultrasonic examination of the attachment integrity for the cutters on the untested S-2B bit, Smith Tool designation SPX-016, which is identical in design and construction to the bit that failed. It is important to determine if the unused bit can be modified and/or repaired in a way that will allow testing at a suitable geothermal site.

Examination of Worn Stratapax™ Drill Blank Cutters from the S-2B, SPX-015, Bit -- Two diamond compact cutters, Nos. 23 and 24, were removed from the bit at Sandia National Laboratories by electrical discharge machining. The machining was done through the cemented tungsten carbide stud so that the braze joint was removed along with the worn diamond compact. Cutters Nos. 23 and 24 were selected because it was apparent from the manner in which the bit wore that these would have been the next two cutters to become detached had the field test not been terminated when it was.

Both cutters had relatively large wear flats that extended past the braze joint into the carbide stud. Considering the short duration of the test, the amount of wear was much greater than would be expected if the loss of diamond material had been due to an abrasive wear mechanism alone. Optical and electron microscopical examination showed that the major loss of diamond was caused by spalling, a tensile fracture failure that starts in the diamond layer at the edge of the cutter and travels roughly parallel to the top surface before turning upward and intersecting the top surface. This type of damage, which is caused by cyclic fatigue and impact loading that exceeds a critical stress level, was investigated in detail by K. Dunn as an earlier part of this program. Spalling was not found to be dependent on temperature over the range of temperatures investigated, 20° to 310°C (68° to 590°F).

The spalling phenomenon generally starts at about one-half to two-thirds of the distance down from the top surface of the diamond layer and extends to the diamond/carbide-substrate interface. Therefore, the cross section of PDC material rubbing against the rock is greatly reduced. Contact stresses are increased, which accelerates the abrasive wear rate. In addition, the heat dissipation is reduced, increasing the likelihood of accelerated wear through localized thermal degradation. Both worn cutters

* Registered Trademark of the General Electric Company, U.S.A.

were checked ultrasonically, and no bulk, thermally-induced degradation was found. However, localized degradation at the rubbing surface cannot be determined by this method.

The braze joints for cutters Nos. 23 and 24 were cut in cross section, polished, and examined metallographically. The joints are representative "LS" bonds that appear to be slightly better than average. There was some porosity in the braze, the braze line widths were slightly greater at one side than at the other, and there was no bonding near the edges of the Stratapax™ drill blanks. There was no visible evidence that the attachment for either sample had been damaged up to the time drilling was discontinued.

The cutters were examined further by optical microscopy and found to have undergone severe localized thermal degradation at the rubbing interface between the sintered PDC layer and the rock formation. Cracks were found in the degraded diamond surface that, together with excessively high stresses, may have initiated the spalling wear mode observed.

A Stratapax™ drill blank that became detached last year at Terra Tek during a hot air laboratory experiment in which granite was drilled was reexamined using the microscopic technique developed for The Geysers' bit cutters. This PDC was also locally thermally degraded.

It is reasonable to conclude for the present stud-type bit designs that air drilling in hot holes does not provide cooling sufficient to avoid localized thermal degrading of the PDC cutters. The reduction in compact strength results in the development of high wear rates and large wear flats that generate sufficient frictional heat to weaken the brazed attachment. The loss of cutters by attachment failure may not be due principally to poor braze joints but may result, as well, from the heating of the braze alloy to a temperature at which the alloy has insufficient strength to resist the forces acting upon it.

Model for The Geysers' Field Test Bit Performance -- Based on the preceding analysis and discussion and on prior field test experience, it is possible to develop a reasonable model for the bit failure and to make some recommendations for future Stratapax™ bit tests in geothermal locations as well as to make some generalizations regarding geothermal, hard rock bit designs.

The bottomhole profile at The Geysers was obviously such that the four gage cutters in the S-2B bit engaged the hard, hot graywacke formation first. In addition, the hole was deviated 25° from vertical, and, because the well was already producing steam, the formation can be presumed to have been fractured. It is very probable that, under these conditions, excessive loading and impact were exerted on individual gage cutters, which resulted in spalling followed by accelerated wear and high frictional heat generation. Under continued cyclic forces at high temperatures, the braze attachments began to fail. As soon as a diamond compact cutter was lost, the cemented carbide stud would wear rapidly, resulting in even more non-uniform loading of the remaining cutters. The process, resulting in cutter loss, repeated itself over and over again, progressing from the periphery of the bit toward the center. At no time were there more than a few cutters in contact with the hard formation.

Although this bit wear rationale may seem speculative, it should be noted that the prior field experience in this program with stud-type bits supports these conclusions. The stud bit that drilled successfully in the Baca field, the S-1, modified design, went into an oversize hole so that the gage cutters did not engage the hard formation first. The main portion of the cutting structure supported the weight when drilling commenced, and, therefore, the load was more uniformly distributed, and no single cutter was prematurely stressed to the failure point. In addition, the bit was cooled with aerated water, which is much more effective than air alone. Although the S-1, modified, bit did exhibit significant wear, including gage wear, the wear was distributed so that effective drilling action was not prevented.

The two 22.2-cm (8-3/4-in.) diameter S-2A bits that were tested in the Baca field were put into a 22.2-cm (8-3/4-in.) hole. Both bits had to ream their way to the bottom. Although a fabrication error in the central portion of the cutting structure of these bits was the principal reason for the ineffective drilling performance, the reaming in the hard volcanic tuff formation plus the overloading of the gage cutters when bottom was reached resulted in excessive cutter stud damage. However, with the aerated water coolant used, the major failure mechanism was not cutter detachment, although some diamond compact spalling was seen.

Additional Testing Recommendations -- The following recommendations were made for further geothermal testing of PDC stud-type bits:

1. Air drilling tests should not be continued until an improved cutter attachment is developed. Considering the high temperatures that can be developed, diffusion bonding may be the best alternative.

2. Geothermal drilling with mud or aerated water still appears feasible if the stud-type bit can be put on the bottom of the hole so that the weight on the bit is relatively uniformly distributed.

- a. One method by which the weight may be distributed evenly is that of lowering the bit into the hole immediately after the casing is set. When this method is used, essentially, the bit is being placed into an oversize hole with the result that the gage cutters engage the rock after the cutters on the crown have begun to drill and are taking most of the thrust force.
- b. A second method for evenly distributing the weight on the bit is that of redesigning the bit so that the rotational stability and, concurrently, the reaming capability of the bit are improved. Where this alternative method is used, the cutters on the central portion of the cutting structure support the weight from the moment of contact between the bit and the bottom of the hole.

Examination of the Untested S-2B Bit, SPX-016 -- All 39 cutters in the principal cutting structure plus the four gage trimmers were ultrasonically tested for (1) braze attachment integrity and (2) evidence of bulk thermal damage that might have occurred during brazing.

The tests revealed two braze attachments that should be replaced, three that were marginal, and four that may be questionable but probably would meet the 365-MPa (53,000-psi) shear strength specification. The two joints requiring replacement were on the -20°-rake experimental design. There was no indication that the braze attachment was damaged in any instance when the studs were press-fitted into the bit body, and there was no evidence of bulk thermal damage in any of the diamond compacts.

It should be noted that the ultrasonic examination was done using a 0.64-cm (1/4-in.) diameter transducer instead of the 1.3-cm (1/2-in.) transducer used for quality control by GE's Specialty Materials Department. The smaller transducer emphasizes localized braze defects because the output signals observed are an average of all the ultrasonic reflections in the area of the bond under the transducer. Therefore, the criteria for braze bond acceptability or rejection used by the Specialty Materials Department do not apply directly to the ultrasonic examination made by CRD. However, the conclusions drawn from the ultrasonic tests are considered valid because the region in which the bonds were examined is the area nearest the cutter tip.

This bit can be repaired by using electrical discharge machining to remove those studs which have poor cutter attachments, and other cutters can be mounted in their place. The capability to use this technique is in place both at GE/CRD, Schenectady, New York, and at Smith Tool, Irvine, California. Smith Tool has experience in this operation.

The S-2B, SPX-016, bit has been shipped to the Sandia National Laboratories for ultrasonic examination of the cutter braze joints. The data obtained from the ultrasonic examination of this bit carried out by GE/CRD have been forwarded to Sandia for comparison with Sandia's prospective data.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>PDC WEAR MECHANISMS</u>													
<u>TEST SUPPORT:</u>													
<u>GENERAL ELECTRIC</u>													
EFFECTS OF DRILLING FLUIDS													
ROCK-FRACTURE /CUTTER- WEAR CONSULTATION													
FINAL REPORT													

LEGEND: ——— ACTIVITY PERIOD
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○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.3 Wear Mechanisms for Polycrystalline Diamond Compacts as Utilized for Drilling in Geothermal Environments

Contractor: General Electric Company, Corporate Research and Development (GE/CRD)
Principal Investigator: L. E. Hibbs, Jr. (518) 385-8330
Contract Period: 16 November 1979 to 30 April 1981
Contract Number: 13-9406 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to provide technical assistance during Sandia's evaluation of the performance of polycrystalline diamond compacts (PDCs) in drill bits designed for use in geothermal environments. The technical support will concern (1) the determination of the effects of drilling fluids on the required cutting force, wear mechanisms, and wear rates of PDC cutters and (2) consultation on rock fracture and cutter wear mechanisms in the development of a model of the rock fracture mechanism as a function of cutting edge configuration.

Project Status

The coordination of the project activities with related work and participating organizations was completed, as was the preparation of the test facilities and equipment. Thirty-four single-cutter experiments have been completed on Nugget sandstone and Tennessee marble. Ten of these experiments were performed on Tennessee marble, using Stratapax™ cutters that contained thermocouples to measure the temperature in various areas of the cutter.

Four tests have been successfully performed in which Tennessee marble was cut with a preground Stratapax™ drill blank containing five thermocouples. Temperature and force component data were collected at cutting speeds of 26.5 and 67.4 m/min (86.9 and 221 ft/min) and at downfeeds of 0.05 and 0.15 mm per revolution (0.002 and 0.006 in. per revolution).

Stratapax™ drill blank cutter wear tests were carried out in which Nugget sandstone was cut. Six tests were run using a coolant, and six tests were run in air. An analysis of the wear test data revealed a linear relationship between the volumetric wear rate and the total distance traveled for the Stratapax™ cutters. In addition, the wear rate in air was found to be 17.6 times greater than the wear rate during cutting with the coolant.

Quarterly Progress

PDC Cutter Temperature Measurement -- Earlier in this program, the feasibility of measuring (1) the temperatures developed near the cutting

interface between a Stratapax™ drill blank and the rock and (2) the temperature developed within the PDC substrate and the supporting tungsten carbide stud was demonstrated. Both sharp and artificially worn cutters were tested cutting Tennessee marble. With each type of cutter, cutting was done with a water-base coolant and in air, i.e., without a coolant. Temperatures were measured using five small thermocouples placed at specific locations within the cutters. The thermocouple junction locations are shown in Figures 4-2 and 4-3.

These preliminary experiments clearly demonstrated the marked difference in frictionally generated heat for sharp and worn cutters and the even more significant increase in temperature when the rock was cut without a coolant. During a test using a diamond compact cutter with a ground wear flat, sufficient heat was developed so that the strength of the Easy Flo-45 brazing alloy bond between the cutter and stud was reduced, and therefore, the bond failed. The point at which the braze attachment failed is clearly shown in Figure 4-4. These experiments were conducted on a vertical turret lathe that cut a spiral path in the surface of a three-foot-square block of marble. Consequently, the cutting speed was continually changing over the duration of each test. After a meeting at Sandia National Laboratories, it was decided that the experimental procedure should be modified, if possible, to maintain a constant cutting speed throughout each test so as to reach an equilibrium temperature distribution within the tool for each set of cutting parameters and diamond compact tool wear conditions chosen. Equilibrium heat flow conditions are necessary for the provision of temperature measurements suitable for testing the cutter temperature model proposed.

It is necessary to use a massive machine such as a large vertical turret lathe in order to provide sufficient thrust to penetrate a rock with worn diamond compact cutters. Only by performing a "plunge" cut on a circular cutting path can the constant speed requirement be met. However, plunging into the rock with a circular cutter produces a groove with constantly increasing width until the diameter of the cutter is reached. At the same time, the contact area between the tool and the rock continually increases. A constant, known contact area is an additional requirement to producing measurements suitable to test the Ortega model. This condition was achieved by the preparing of a standing circular ridge in the surface of the rock specimen. The ridge width was essentially equal to the width of the cutting edge of the wear flat that was ground on the PDC; the nominal ridge width was 8.18 mm (0.322 in.) for the experiment described below. Thus, the required conditions of constant speed and constant apparent cutter/rock contact area were achieved by the performing of what metal machinists term "orthogonal" cutting. A sketch of the cross section of the rock with the ridge to be cut away is shown in Figure 4-5.

• Experimental Details and Results

Four cutting tests have been performed, and the results indicate that this method of testing is a viable experimental technique. The configuration and dimensions of the wear flat ground on the Stratapax™ drill blank cutter are shown in Figure 4-6. The wear flat is a portion of an ellipse, and its area (K_E) can be calculated exactly by

Figure 4-2. Thermocouple Locations for a Sharp Stratapax™ Drill Blank Cutter and Stud

Figure 4-3. Thermocouple Locations for a Dull Stratapax™ Drill Blank Cutter and Stud; Wearback = 0.047 in.; Wear Flat Area = 0.030 in.²

Figure 4-4. Temperatures Developed in Stratapax™ Drill Blank Cutter No. 8 Cutting Tennessee Marble. The Easy Flo-45 braze alloy bond failed at ~380°C. The vertical thrust force acting on the diamond compact was 800lb at the moment of failure.

Figure 4-5. Cross Section through Rock Showing Standing Circular Ridge Prepared for Cutting Temperature Experiments

WEAR FLAT AREA

$$\begin{aligned}
 K_p &= \frac{4}{3}(d)\left(\frac{w}{2}\right) \\
 &= \frac{4}{3}(0.145)\left(\frac{0.311}{2}\right) \\
 &= 0.030 \text{ in.}^2
 \end{aligned}$$

BOTTOM VIEW OF
WEAR FLAT

MEASURED WEAR FLAT
DIMENSIONS, CUTTER NO. 8

Figure 4-6. Stratapax™ Drill Blank Cutter/Rock Configuration Used for Cutting-Temperature Measurements and Calculation of Ground Wear Flat Area for Cutter No. 8

$$\frac{K_E}{2} = \int_{A-d}^A \frac{B}{A} \sqrt{A^2 - x^2} dx, \quad (1)$$

where A is one-half of the major axis of the ellipse and B is one-half of the minor axis.

The solution of Eq. (1) is

$$K_E = \frac{B}{A} \left[x \sqrt{A^2 - x^2} + A^2 \sin^{-1} \left(\frac{x}{A} \right) \right]_{A-d}^A. \quad (2)$$

Using the nominal diameter for a Product No. 2530 Stratapax™ drill blank of 13.3 mm (0.524 in.) and a cutter back-rake angle of 20°,

$$A = \frac{0.524 \text{ in.}^*}{2 \sin 20^\circ}. \quad (3)$$

B in Eq. (1) is equal to the radius of the cutter, 6.65 mm (0.262 in.), and d can be calculated from the wearback (w):

$$d = \frac{w}{\sin 20^\circ}. \quad (4)$$

Eq. (1) is somewhat cumbersome to use. A very close estimate of the wear flat area can be made by assuming it is the area bounded by a parabola, as shown in Figure 4-6. This area, K_P , is estimated by

$$K_P = \frac{4}{3} (d) \left(\frac{l}{2} \right), \quad (5)$$

or

* Throughout this study, measurements were made in inches, and, consequently, inches were used in the equations. The use of inches has been retained in the equations included in this subsection in order to maintain authenticity.

$$K_P = \frac{2d\ell}{3}.$$

For Eq. (5), ℓ can be calculated from the nominal dimensions of the No. 2530 Stratapax™ drill blank and the wearback (w):

$$\ell = 2\sqrt{(0.262 \text{ in.})^2 - (0.262 \text{ in.} - w)^2} \quad (6)$$

Alternatively, the d and ℓ dimensions can be determined with a measuring microscope or a low-power microscope equipped with a calibrated Filar eyepiece. This is the technique that was used for the preliminary rock-cutting temperature experiments that have been performed to date. The relationship between the exact area calculation (K_E) and the approximated area calculation (K_P) as a function of wearback (w) is shown in Table No. 4-1. This approximation appears to be adequate.

Table 4-1

Comparison of the Approximate Wear Flat Area and the Exact Wear Flat Area as a Function of Wearback.

Wearback, w		Wear Flat Length, d		Exact Area, K_E		Approximate Area, K_P		K_P/K_E
mm	(in.)	mm	(in.)	mm ²	(in ²)	mm ²	(in ²)	
0.254	(0.0100)	0.742	(0.0292)	1.81	(0.0028)	1.81	(0.0028)	1.000
0.508	(0.0200)	1.486	(0.0585)	5.10	(0.0079)	5.10	(0.0079)	1.000
0.762	(0.0300)	2.228	(0.0877)	9.29	(0.0144)	9.16	(0.0142)	0.986
1.016	(0.0400)	2.972	(0.1170)	14.26	(0.0221)	14.00	(0.0217)	0.981

Four successful cutting tests have been performed cutting Tennessee marble with cutter No. 8, a preground Stratapax™ drill blank having five thermocouples located in the positions shown in Figure 4-3. Two tests were run at 67.4 m/min (221 ft/min) and two at 26.5 m/min (86.9 ft/min). At each cutting speed, one test was performed at 0.05 mm per revolution (0.002 in. per revolution) downfeed and one test at 0.15 mm per revolution (0.006 in. per revolution) downfeed. A water-soluble oil coolant, 40:1 water to oil, was used at a 0.024-m³/min (6.3-gal/min) flow rate impinging directly on the circular face of the cutter. Each test was run long enough for the measured temperatures to reach their maximum values, attaining equilibrium. In addition to the temperature data, the three mutually perpendicular forces acting on the cutter were obtained. The time, five temperatures, and three forces were sampled sequentially by a data logger and recorded on magnetic tape. A complete data set was obtained every 2 seconds for the duration of each cut.

The results of these four cutting experiments are summarized in Table 4-2. Cutter No. 8 had a preground wear flat area of 0.19 cm^2 (0.030 in.^2). The highest temperature observed, approximately 161°C (258°F), was obtained during the highest speed/highest downfeed test, as might be anticipated. The temperatures produced were more responsive to speed changes than to changes in cutter engagement. Note that the three-fold change in downfeed did not produce a corresponding proportional change in thrust or cutting force. Based on GE's prior rock-cutting experience, such a change was not expected. The effectiveness of the water as compared to air in reducing the temperatures near the rock-cutting interface is clearly shown by the results of these tests. How much of the role of the fluid is cooling and how much is reduction in the frictional forces that are converted to heat is not evident yet. Additional experiments should provide some clarification.

There was no measurable wear of cutter No. 8 after these experiments. The very modest temperatures developed together with the nonabrasive character of the Tennessee marble did not produce any significant tool wear. This cutter still is usable for additional experiments of this type.

These experimental results were reviewed at Sandia National Laboratories on 27 January 1981. The experimental method was considered satisfactory, and specific additional tests have been planned. Although the primary need is for Stratapax™ less drill blank wear information, it was decided that the wear tests should be halted temporarily to carry out the following experiments, which should provide enough information for a preliminary test of the temperature model:

1. Test No. 45 (See Table 4-2) will be repeated to obtain a temperature data point for thermocouple position A.
2. The four cutting conditions shown in Table 4-2 will be repeated using a sharp, preground cutter with a straight cutting edge the same length as that of cutter No. 8 but having a 20° end clearance instead of a wear flat so that the end will not rub against the rock surface. Only forces will be measured, not temperatures. This experiment should provide the information necessary to estimate what portion of the measured cutting force for the dull, i.e., the worn, tool tests is the friction force and what portion is the actual cutting force.
3. A second set of four cutting tests will be carried out with cutter No. 8 under identical conditions as the first set, tests Nos. 45 to 48, but with a markedly reduced fluid flow rate, so that higher temperatures will be generated. Preliminary tests may have to be done to determine the optimum reduced fluid flow rate. Air cuts will be done only as a last resort.
4. A set of base line tests under the same conditions as those described in experiment No. 3 above will be performed using the sharp preground cutter, measuring forces only, to provide information for estimating frictional and true cutting forces.

Table 4-2

Results of Plunge Cut Tests with Stratapax™ Drill Blank Cutter No. 8 on Tennessee Marble, Using 40:1 Water-Soluble Oil Coolant at a 0.24-m³/min (6.3-gal/min) Flow Rate Directed Against the Circular Face of the Cutter

					Thermocouple Positions					Cutting Forces		
					A	B	C	D	E			
					Temperature Average							
Test No.	rpm	Cutting Path Radius cm (in.)	Cutting Speed m/min (ft/min)	Downfeed mm/rev (in./rev)	°C (°F)	°C (°F)	°C (°F)	°C (°F)	°C (°F)	Side, F _N (lb) ^x	Vertical, F _y N (lb)	Cutting, F _z N (lb)
45	30.15	35.56 (14)	67.36 (221.0)	0.152 (0.006)	*	160.9 (224.4)	80.8 (177.4)	48.1 (118.6)	26.6 (80.0)	19.1 (4.3)	1,512 (339.9)	495 (111.3)
46	30.15	35.56 (14)	67.36 (221.0)	0.051 (0.002)	106.0 (222.8)	100.4 (212.7)	73.0 (163.4)	42.5 (108.5)	27.8 (82.0)	40.0 (9.0)	1,452 (326.5)	353 (79.4)
47	12.64	33.34 (13-1/8)	26.49 (86.9)	0.051 (0.002)	72.0 (161.6)	63.6 (146.5)	43.0 (109.4)	31.1 (88.0)	24.4 (75.9)	35.6 (8.0)	1,353 (304.1)	222 (50.0)
48	12.64	33.34 (13-1/8)	26.49 (86.9)	0.152 (0.006)	85.9 (186.6)	75.7 (168.3)	47.9 (118.2)	31.5 (88.7)	24.1 (75.4)	43.1 (9.7)	1,572 (353.4)	433 (97.3)

Note: Preground wear flat area on Cutter No. 8 = 0.19 cm² (0.030 in.²)

* Thermocouple moved

PDCs Wear Tests -- PDCs can wear by several different mechanisms, ranging from abrasive microchipping at the lowest wear rate end of the scale to catastrophic, thermally induced wear at the highest wear rate end of the scale. Consequently, it was determined that laboratory wear tests should not be performed in a greatly accelerated manner if the wear modes and rates developed are to be those predicted for cutters on bits subjected to equivalent rock cutting parameters of speed, cutter engagement, and fluid environment, or lack thereof in the case of air drilling. Another consideration was that the growth of a wear scar and the shape it will have at any stage in its growth will be dependent upon the particular rock cutting parameters being used. For this reason, artificially generating the bulk of the desired wear by a fast method such as grinding prior to the rock cutting test may not produce reliable results. Wear rates and wear modes at different stages of wear should be determined by starting with sharp cutters. For this reason, laboratory wear rate tests are very time consuming.

The wear results reported here were obtained by the cutting of a 0.9 by 0.9 by 0.46 meter (3 by 3 by 1-1/2 foot) block of Nugget sandstone, using the 54-inch, vertical turret lathe adapted for rock cutting studies. Facing cuts were performed on the 0.9 by 0.9 meter (3 by 3 foot) surface of the rock. The PDC cutters used were Product No. 2530 Stratapax™ drill blanks brazed on the standard 20° negative rake cemented tungsten carbide stud. The usual 5° end clearance for the carbide stud was increased to 20° for all cutters to prevent the stud from engaging the rock except by the development of a wear scar. The side rake for all tests was zero.

A cutter that traverses the entire face of a 0.9 meter (3-foot) diameter rock will undergo a large change in cutting speed if the lathe is operated at a constant rotary speed. In order to maintain a constant average speed within a relatively small speed range for each cutter, the face of the rock was divided into six concentric rings, or bands, each 2 inches wide. Each band was physically separated from its neighbors by a groove produced by a plunge cut with a Stratapax™ drill blank tool. Every PDC cutter being tested was assigned to a particular band and was used to cut rock only from this band. Table 4-3 gives the positions of the concentric bands used, each band's inside and outside radius, and the maximum, minimum and average cutting speeds obtained at 50.24 rpm. The average speeds for a set of six cutters ranged from a maximum of 135 m/min (443 ft/min) on band No. 1 to a minimum of 31.7 m/min (104 ft/min) on band No. 6.

All the wear tests to date have been performed at 50.24 rpm, at a crossfeed of 0.305 mm (0.012 in.) per revolution, and with a cut 0.508 mm (0.020 in.) in depth. A single pass across each band takes 3.25 minutes at this rotary speed and crossfeed. The distance traveled by the cutter relative to the rock becomes progressively less from band No. 1 to band No. 6.

Depending upon the rate of wear, each cutter was removed from the test situation after it made a predetermined number of passes across its assigned band, and the wear scar was photographed and measured. Cutting, normal, and side thrust forces were determined using a piezoelectric dynamometer for the pass made just prior to the taking of each wear measurement.

Table 4-3

Locations of the Six 5.08-cm (2.0-in.) Wide Concentric Circular
Bands Used for Stratapax™ Drill Blank Wear Tests Cutting
Nugget Sandstone and the Cutting Speeds at 51.24 rpm

Band No.	Outside Radius cm (in.)		Inside Radius cm (in.)		Cutting Speed		
					Maximum m/min (ft/min)	Minimum m/min (ft/min)	Average m/min (ft/min)
1	44.450	(17.500)	39.370	(15.500)	143.0 (470)	127.0 (416)	135.0 (443)
2	38.039	(14.976)	32.959	(12.976)	123.0 (402)	106.0 (348)	114.0 (375)
3	31.628	(12.452)	26.548	(10.452)	102.0 (334)	85.3 (280)	93.6 (307)
4	25.217	(9.928)	20.137	(7.928)	112.0 (266)	64.9 (213)	73.2 (240)
5	18.806	(7.404)	13.726	(5.404)	60.7 (199)	44.2 (145)	52.4 (172)
6	12.395	(4.880)	7.315	(2.880)	39.9 (131)	23.6 (77.3)	31.7 (104)

The measurements necessary for the calculating of the wear volume and the wear scar area are shown in Figure 4-7. Note that two different cases are shown; case A, where the wear is confined to the sintered diamond layer and case B, where the wear scar has progressed into the drill blank cemented tungsten carbide substrate. All wear measurements were made using a Filar eyepiece on a low-power microscope.

Referring to Figure 4-7, the diamond wear volume (B) for case A was calculated from

$$V \cong \left[\frac{0.21565\theta}{360} - 0.03432 \sin \theta \right] t \cos \phi , \quad (7)$$

where

$$\theta = 2 \sin^{-1} \left(\frac{W_2}{0.524} \text{ in.} \right) \text{ and}$$

$$\phi = \text{rake angle} .$$

The wear scar of wear flat area (A_{D_1}) for case A was estimated by

$$A_{D_1} \cong \frac{2}{3} tw_1 . \quad (8)$$

For case B, where the wear scar extends into the diamond compact tungsten carbide substrate, the diamond wear volume (V) was also calculated using Eq. (7). However, referring to Figure 4-7, for case B,

$$\theta = 2 \sin^{-1} \left(\frac{W_4}{0.524} \text{ in.} \right) , \quad (9)$$

where

$$W_4 = \frac{W_1 + W_3}{2} .$$

Figure 4-7. Measurements Made To Calculate Wear Volume and Wear Scar Areas for Stratapax™ Drill Blank Cutters

For case B, the total wear scar or wear flat area (A_T), including both diamond and tungsten carbide, is

$$A_T \cong \frac{2}{3} dw_1 . \quad (10)$$

The diamond wear flat area (A_D) can be calculated as the difference between the total area (A_T) and the area of the wear scar on the carbide substrate (A_{wc}); this calculation can be made in the following two ways:

either

$$A_D = A_T - A_{wc} , \quad (11)$$

where

$$A_{wc} \cong \frac{2}{3} (d-t) (w_3) , \quad (12)$$

or

$$A_{D_2} \cong W_4 t . \quad (13)$$

The calculated wear volume, wear scar areas, and forces acting on the cutter were recorded, and the total cutting time, total distance traveled by the cutter, volume of rock removed, and specific energy were calculated. The specific energy (S.E.) in ft-lb/in.³ is

$$S.E. = \frac{F D}{V_R} , \quad (14)$$

where

F is the cutting force,
 D is the distance traveled by the cutter in making the pass across a 5.08-cm (2-in.) band, and
 V_R is the volume of rock removed per pass.

• Experimental Results

Wear tests have been carried out cutting Nugget sandstone with a 40:1 water-soluble oil coolant and in still air. A set of six Stratapax™ drill blank cutters was used for each cutting environment, i.e., dry and wet. Where the coolant was used, the flow rate was 0.024 m³/min (6.3 gal/min). Specific experimental conditions for each cutter are given in Tables 4-4 and 4-5.

For the tests conducted with the water-base coolant, in which cutters Nos. W-1 through W-6 were used, each cutter was run for a total of 40 passes across its assigned band on the Nugget sandstone. The experimental results of these tests are summarized in Table 4-6. An explanation of the data column headings for this table and also for Table 4-7 can be found in Table 4-8.

Microscopic examination of the wear scars for the cutters run with coolant showed no evidence of accelerated wear due to thermal effects. The wear mode was the typical microchipping of individual diamond crystallites making up the sintered diamond layer. There was no evidence of spalling or delamination failure. Because only one wear mechanism was observed to be operational for this set of tests, the volumetric wear should be directly proportional to the distance traveled, independent of the cutting speed. Figure 4-8 shows the wear volume data plotted as a function of total distance traveled. The solid line in Figure 4-8 represents the best straight-line fit to the data. The W-6 data point at the 3,050-meter (10,000-foot) length of cut was suspect and not included in the regression analysis. The correlation coefficient for the analysis was 0.91245, and the slope, which is the volumetric wear rate when Nugget sandstone is cut, using the water-base coolant, was 1.015×10^{-8} cm³/m (1.887×10^{-10} in.³/ft). Theoretically, the line should pass through the zero-wear/zero-distance point. There are several reasons why this does happen in practice.

1. The errors inherent in measuring and calculating wear volume will be greatest for very small amounts of wear.
2. The edges of the Stratapax™ drill blank cutters are not perfect to begin with. There is always some chipping and rounding of the edge, which will be included in the measurements.
3. There may be some damage resulting from the shaping process that weakens the edge. This damage will be superficial but will result in initially accelerated wear.

Wear tests have been run for a total of 10 passes for each cutter, in which Nugget sandstone was cut in air, i.e., without coolant, with diamond compact cutters Nos. W-7 through W-12. The results of these experiments are summarized in Table 4-7. Difficulty was encountered in obtaining force measurements when these experiments were begun because of dynamometer drift caused by the conduction of heat from the cutting zone through the tool holder to the piezoelectric crystals. This problem was corrected by the constructing of a tool holder with a cooling coil between the cutter and the dynamometer housing.

Table 4-4

Wear Test Conditions for Stratapax™ Drill Blank Cutters
 Nos. W-1 through W-6 Cutting Nugget Sandstone with
 40:1 Water-Soluble Oil Coolant at a 0.024-m³/min
 (6.3-gal/min) Flow Rate

Cutter No.	Rock Band No.	Average Cutting Speed m/min (ft/min)	Cutting Time per Pass minutes	Length of Cut per Pass meters (feet)	Volume of Rock Removed per Pass cm ³ (in. ³)
W-1	1	135.0 (443)	3.25	438.9 (1,440)	21.63 (1.320)
W-2	2	114.0 (375)	3.25	371.9 (1,220)	18.29 (1.116)
W-3	3	93.6 (307)	3.25	304.6 (999.4)	15.01 (0.916)
W-4	4	73.6 (240)	3.25	237.5 (779.1)	11.70 (0.714)
W-5	5	52.4 (172)	3.25	170.4 (558.9)	8.39 (0.512)
W-6	6	31.7 (104)	3.25	103.2 (338.6)	5.08 (0.310)

Note: Depth of cut for all tests = 0.508 mm (0.020 in.)
 Crossfeed for all tests = 0.305 mm (0.012 in.) per revolution

Table 4-5

Wear Test Conditions for Stratapax™ Drill Blank Cutters Nos. W-7
 through W-12 Cutting Nugget Sandstone Dry (in Air)

Cutter No.	Rock Band No.	Average Cutting Speed m/min (ft/min)	Cutting Time per Pass minutes	Length of Cut per Pass meters (feet)	Volume of Rock Removed per Pass cm ³ (in. ³)
W-7	1	135.0 (443)	3.25	438.9 (1,440)	21.63 (1.320)
W-8	2	114.0 (375)	3.25	371.9 (1,220)	18.29 (1.116)
W-9	3	93.6 (307)	3.25	304.6 (999.4)	15.01 (0.916)
W-10	4	73.6 (240)	3.25	237.5 (779.1)	11.70 (0.714)
W-11	5	52.4 (172)	3.25	170.4 (558.9)	8.39 (0.512)
W-12	6	31.7 (104)	3.25	103.2 (338.6)	5.08 (0.310)

Note: Depth of cut for all tests = 0.508 mm (0.020 in.)
 Crossfeed for all tests = 0.305 mm (0.012 in.) per revolution

Table 4-6

Summary of Experimental Wear Test Results for Stratapax™ Drill Blank
Cutters Nos. W-1 through W-6^a

Cutter No.	P	T minutes	N	F _x (lb)	N	F _y (lb)	N	F _z (ft)	V	A _T ^b	D _T	R	S.E.
W-1	1	3.25	26.7	(6.0)	116	(26.0)	44.5	(10.0)	c	c	439	(1,440)	902.58 (10,909)
W-1	10	32.5	85.4	(19.2)	418	(94.0)	86.3	(19.4)	0.0831 (5.07)	1.286 (19.93)	4,390 (14,400)	216.3 (13.20)	1,751.0 (21,164)
W-1	20	65.0	65.8	(14.8)	337	(82.5)	53.4	(12.0)	0.134 (8.17)	1.863 (28.87)	8,780 (28,800)	432.6 (26.40)	1,083.1 (13,091)
W-1	21	68.25	63.2	(14.2)	378	(85.0)	65.8	(14.8)	c	c	9,217 (30,240)	454.2 (27.72)	1,335.8 (16,145)
W-1	30	97.5	69.4	(15.6)	347	(78.0)	55.2	(12.4)	0.163 (9.96)	2.033 (31.51)	13,200 (43,200)	648.9 (39.60)	1,119.2 (13,527)
W-1	40	130	64.9	(14.6)	338	(76.5)	59.6	(13.4)	0.162 (9.89)	2.490 (38.60)	17,600 (57,600)	865.2 (52.80)	1,209.5 (14,618)
W-2	1	3.25	13.3	(3.0)	80.1	(18.0)	32.0	(7.2)	c	c	372	(1,220)	651.1 (7,870)
W-2	10	32.5	28.5	(6.4)	142	(32.0)	39.1	(8.8)	0.0364 (2.22)	0.630 (9.76)	3,720 (12,200)	182.9 (11.16)	795.9 (9,620)
W-2	20	65.0	32.9	(7.4)	176	(39.5)	44.5	(10.0)	0.0810 (4.94)	0.916 (14.20)	7,440 (24,400)	365.8 (22.32)	904.5 (10,932)
W-2	30	97.5	56.0	(12.6)	245	(55.0)	53.4	(12.0)	0.119 (7.27)	1.259 (19.51)	11,200 (36,600)	548.6 (33.48)	1,085.3 (13,118)
W-2	40	130	64.9	(14.6)	296	(66.5)	48.9	(11.0)	0.193 (11.76)	1.543 (23.92)	14,900 (48,800)	731.5 (44.64)	994.91 (12,025)
W-3	1	3.25	15.1	(3.4)	70.3	(15.8)	28.5	(6.4)	c	c	304.6	(999.4)	577.8 (6,983)
W-3	10	32.5	26.7	(6.0)	133	(30.0)	41.8	(9.4)	0.0208 (1.27)	0.525 (8.14)	3,046 (9,994)	150 (9.16)	848.6 (10,256)
W-3	20	65.0	22.2	(5.0)	133	(30.0)	30.2	(6.8)	0.0595 (3.63)	0.765 (11.85)	6,092.3 (19,988)	300.2 (18.32)	613.8 (7,419)
W-3	30	97.5	33.8	(7.6)	145	(32.5)	41.8	(9.4)	0.0993 (6.06)	0.935 (14.50)	9,138.5 (29,982)	450.3 (27.48)	848.55 (10,256)
W-3	40	130	31.1	(7.0)	165	(37.0)	40.9	(9.2)	0.118 (7.18)	1.087 (16.85)	12,185 (39,976)	600.4 (36.64)	830.51 (10,038)
W-4	1	3.25	18.7	(4.2)	53.4	(12.0)	40.9	(9.2)	c	c	237.5	(779.1)	830.60 (10,039)
W-4	10	32.5	19.6	(4.4)	103	(23.2)	40.9	(9.2)	0.0198 (1.21)	0.457 (7.08)	2,375 (7,791)	117 (7.14)	830.60 (10,039)
W-4	11	35.75	24.9	(5.6)	127	(28.5)	37.4	(8.4)	c	c	2,612 (8,570)	129 (7.85)	758.4 (9,166)
W-4	12	39.0	26.7	(6.0)	138	(31.0)	36.5	(8.2)	c	c	2,850 (9,349)	140 (8.57)	740.3 (8,948)
W-4	20	65.0	35.6	(8.0)	160	(36.0)	50.7	(11.4)	0.0578 (3.53)	0.8735 (13.54)	4,749.3 (15,582)	234.0 (14.28)	1,029.2 (12,439)
W-4	30	97.5	59.6	(13.4)	292	(65.6)	79.2	(17.8)	0.0744 (4.54)	1.342 (20.00)	7,124.0 (23,373)	351.0 (21.42)	1,607.0 (19,423)
W-4	40	130	56.9	(12.8)	302	(68.0)	58.7	(13.2)	0.0795 (4.85)	1.552 (24.05)	9,498.8 (31,164)	468.0 (28.56)	1,191.7 (14,404)
W-5	1	3.25	13.3	(3.0)	85.4	(19.2)	32.0	(7.2)	c	c	170.4	(558.9)	650.2 (7,859)
W-5	10	32.5	19.6	(4.4)	131	(29.5)	32.0	(7.2)	0.0188 (1.15)	0.488 (7.56)	1,704 (5,589)	83.9 (5.12)	650.2 (7,859)
W-5	20	65.0	29.4	(6.6)	145	(32.5)	41.8	(9.4)	0.0460 (2.81)	0.557 (8.64)	3,407.0 (11,178)	167.8 (10.24)	848.97 (10,261)
W-5	30	97.5	31.1	(7.0)	156	(35.0)	38.3	(8.6)	0.0901 (5.50)	0.8103 (12.56)	5,110.5 (16,767)	251.7 (15.36)	776.7 (9,388)
W-5	40	130	36.5	(8.2)	167	(37.5)	36.5	(8.2)	0.0126 (7.71)	1.006 (15.60)	6,814.1 (22,356)	335.6 (20.48)	740.6 (8,951)
W-6	1	3.25	15.1	(3.4)	91.6	(20.6)	32.0	(7.2)	c	c	103.2	(338.6)	650.6 (7,864)
W-6	10	32.5	17.8	(4.0)	125	(28.0)	33.8	(7.6)	0.0213 (1.30)	0.392 (6.07)	1,032 (3,386)	50.8 (3.10)	686.8 (8,301)
W-6	20	65.0	26.7	(6.0)	136	(30.5)	36.5	(8.2)	0.0370 (2.26)	0.530 (8.22)	2,064 (6,772)	102 (6.20)	741.1 (8,957)
W-6	30	97.5	31.1	(7.0)	147	(33.0)	38.3	(8.6)	0.0883 (5.39)	0.8110 (12.57)	3,096.2 (10,158)	152 (9.30)	777.1 (9,393)
W-6	30	130	32.9	(7.4)	156	(35.0)	37.4	(8.4)	0.0739 (4.51)	0.8852 (13.72)	4,128.2 (13,544)	203 (12.40)	759.1 (9,175)

^aRefer to Table 4-8 for explanations of column headings and to Table 4-4 for Test Conditions

^bEqual to A_{D1}

^cNegligible reading

Table 4-7

Summary of Experimental Wear Test Results for Stratapax™ Drill Blank Cutters Nos. W-7 Through W-12^a

Cutter No.	P	T minutes	N F_x (lb)	N F_y (lb)	N F_z (ft)	V mm ³ (in. ³ x 10 ⁻⁴)	A_T mm ² (in. ² x 10 ⁻⁴)	A_{WC} mm ² (in. ² x 10 ⁻⁴)
W-7	10	32.5	b	b	b	0.8972 (54.75)	1.326 (80.94)	0.1958 (11.95)
W-8	10	32.5	b	b	b	0.9001 (54.93)	1.215 (74.16)	0.3533 (21.56)
W-9	5	16.25	b	b	b	0.4698 (28.67)	0.6194 (37.80)	b
W-9	6	19.5	158 (35.5)	765 (172)	222 (50.0)	0.4775 (29.14)	0.6325 (38.60)	b
W-9	10	32.5	156 (35.0)	890 (200)	260 (58.5)	0.7140 (43.57)	1.037 (63.29)	0.2065 (12.60)
W-10	1	3.25	36 (8.2)	220 (49.5)	72.1 (16.2)	0.0706 (4.31)	0.1994 (12.17)	b
W-10	5	16.25	125 (28.0)	818 (184)	209 (47.0)	0.3425 (20.90)	0.4914 (29.99)	b
W-10	10	32.5	140 (31.5)	912 (205)	280 (63.0)	0.8575 (52.33)	0.9003 (54.94)	0.1650 (10.07)
W-11	1	3.25	36 (8.0)	193 (43.5)	77.4 (17.4)	0.0649 (3.96)	0.1827 (11.15)	b
W-11	5	16.25	127 (28.5)	756 (170)	187 (42.0)	0.3597 (21.95)	0.4888 (29.83)	b
W-11	10	32.5	133 (30.0)	965 (217)	265 (59.5)	0.5683 (34.68)	0.8436 (51.48)	0.1442 (8.80)
W-12	1	3.25	41 (9.2)	200 (45.0)	82.7 (18.6)	0.0600 (3.66)	0.1386 (8.46)	b
W-12	5	16.25	105 (23.5)	601 (135)	182 (41.0)	0.2352 (14.35)	0.3918 (23.91)	b
W-12	10	32.5	182 (41.0)	1,250 (280)	289 (65.0)	0.3388 (20.68)	0.6573 (40.11)	0.0

Cutter No.	A_D mm ² (in. ² x 10 ⁻⁴)	A_{D2} mm ² (in. ² x 10 ⁻⁴)	D_T meters (feet)	R cm ³ (in. ³)	J/cm^3	S.E. (ft*lb/in. ³)
W-7	1.131 (68.99)	1.095 (66.83)	4,389 (14,400)	216.3 (13.20)	b	
W-8	0.8620 (52.60)	0.9282 (56.64)	3,719 (12,200)	182.9 (11.16)	b	
W-9	0.6194 (37.80)	b	1,523 (4,997)	75.1 (4.58)	b	
W-9	0.6325 (38.60)	b	1,826 (5,996)	90.1 (5.50)	4,513.4	(54,552)
W-9	0.8307 (50.69)	0.8600 (52.48)	3,046 (9,994)	150 (9.16)	5,280.8	(63,826)
W-10	0.1994 (12.17)	b	237.5 (779.1)	6.54 (0.714)	1,462.5	(17,677)
W-10	0.4914 (29.99)	b	1,188 (3,896)	58.5 (3.57)	4,243.2	(51,285)
W-10	0.7353 (44.87)	0.8941 (54.56)	2,375 (7,791)	117 (7.14)	5,522.2	(66,744)
W-11	0.1827 (11.15)	b	170.4 (558.9)	8.39 (0.512)	1,571.5	(18,994)
W-11	0.4888 (29.83)	b	851.9 (2,795)	42.0 (2.56)	3,793.2	(45,847)
W-11	0.6994 (42.68)	0.7296 (44.52)	1,704 (7,791)	33.9 (5.12)	5,373.8	(64,950)
W-12	0.139 (8.46)	b	103.2 (338.6)	5.08 (0.310)	1,680.9	(20,316)
W-12	0.3918 (23.91)	b	516.0 (1,693)	25.4 (1.55)	3,705.2	(44,783)
W-12	0.6573 (40.11)	0.6738 (41.12)	1,032 (3,386)	50.8 (3.10)	5,874.1	(70,997)

^aRefer to Table 4-8 for explanation of column headings and to Table 4-4 for test conditions.^bData not taken.

Table 4-8

Data Column Headings for Tables 4-6 and 4-7

Column Heading	Name	Calculation Used
P	Total no. of passes	N.A.
T	Total cutting time	$T = 2.25P$
F_x	Side force	N.A.
F_y	Vertical thrust force	N.A.
F_z	Cutting force	N.A.
V	Diamond wear volume	$V \approx \left(\frac{0.21565\theta}{360^\circ} - 0.0342 \sin \theta \right) t \cos \phi$
A_T	Total wear area	$A_T \approx \frac{2}{3}(tw_1)$ or $A_T \approx \frac{2}{3}(dw_1)$
A_{wc}	Cemented carbide wear area	$A_{wc} \approx \frac{2}{3}(d - t)(w_3)$
A_{D1}	Diamond wear area	$A_{D1} \approx A_T - A_{wc}$
A_{D2}	Diamond wear area	$A_{D2} \approx w_4 t$
D_T	Total distance traveled by cutter	$D = D \times P$ $(D = \text{distance/pass})$
R	Total volume of rock removed	$R = V_R \times P$
S.E.	Specific Energy	$S.E. = F_z D / V_R$

N.A. = not applicable

Figure 4-8. Wear Volume as a Function of Distance Cut for Cutters Nos. W-1 through W-6, Cutting Nugget Sandstone with a Water-Base Coolant of 40:1 Water-Soluble Oil at a Flow Rate of 0.024 m³/min (6.3 gal/min)

The wear rate for the dry, i.e., air, cuts was markedly greater than the rate obtained using the coolant. Microscopic examination of the wear scars showed that the wear mode was no longer simple abrasive microchipping but was, apparently, a combination of two wear mechanisms in which elevated temperatures caused by frictional heat played a role. Cutter No. W-7 is the diamond compact that was tested at the highest speed, 135 m/min (443 ft/min), and the entire wear scar showed evidence of the onset of gross thermal degradation. There was visible evidence of the pullout of diamond crystals and of cracks surrounding individual grains, which indicated the failure of bonds at the grain boundaries, and there were signs of incipient delamination; however, no actual delamination and spalling of the diamond compact layer had occurred. On the other hand, cutter No. W-12, which was tested at 31.7 m/min (104 ft/min), the lowest speed of the set of six cutters, showed a different type of wear. Almost every diamond grain was worn flat, in effect, almost polished, but there was no evidence that the structural integrity of the sintered compact had been damaged. There were no cracks between diamond grains, and there was no conclusive evidence of crystal pullout. The four cutters run at speeds between 135 and 31.7 m/min (443 and 104 ft/min) showed both of the types of wear described previously, with "polishing" wear at the edges of the wear scar and thermal-degradation damage at the center where the temperature was the highest.

All the volumetric wear data, independent of speed, have been plotted in Figure 4-9 as a function of the total distance traveled for each diamond compact cutter. The solid line in the figure represents the excellent straight-line fit that was obtained for most of these data, which have a correlation coefficient of 0.98644 and a slope, representing the wear rate, of $1.785 \times 10^{-7} \text{ cm}^3/\text{m}$ ($3.320 \times 10^{-9} \text{ in.}^3/\text{ft}$). The wear rate during the cutting of Nugget sandstone in air was 17.6 times greater than the wear rate using the coolant.

The fact that these air-cutting wear data even approximate a linear function of distance cut is surprising because there are at least two wear modes operative. However, only a limited number of tests have been performed, and additional results may show that the relationship is not truly linear. The wear measurements that must be used, i.e., the measuring of wear scars that only approximate the ideal geometries on which the calculations are based, are unavoidably inaccurate, leading to a large amount of scatter in the experimental results. Also, the nature of the "polishing" mode of wear is not yet understood and requires further investigation. Until the nature of all the operative wear mechanisms is understood, it cannot be said which is rate controlling; therefore, the relationship between wear and other variables of the cutting system should not be speculated upon.

The role of the fluid in reducing the wear rate of the PDCs is dramatic. The relatively severe thermal degradation of cutters run in air shows that the primary effect of a water-base fluid is to reduce the temperature of the drill blanks, particularly in the cutting zone and especially at the diamond/rock rubbing interface. One reason, perhaps the major reason, for the temperature reduction is the superior heat transfer capabilities of the fluid compared to air. But the fluid used in these experiments, 40:1 water-soluble oil, may have additional beneficial effects. A comparison of the measured cutting forces given in Table 4-6 and

Figure 4-9. Wear Volume as a Function of Distance Cut for Cutters Nos. W-7 through W-12 Cutting Nugget Sandstone in Air

Table 4-7 shows that these forces are markedly lower for the tests run with coolant as compared with those conducted in air. In particular, from a comparison of the forces for cutter pairs W-4 and W-10, W-5 and W-11, and W-6 and W-12 as measured for the first pass, when the cutting edges were still sharp, it is apparent that the fluid has an additional function, or functions, other than that of acting only as an efficient heat exchange medium.

The coolant tends to flood the entire surface of the rock during the cutting tests. Because the Nugget sandstone has some porosity and the fluid has a finite residence time in contact with the rock before the rock is cut, the fluid, containing a small amount of oil, can penetrate the rock pores, probably to a depth greater than the 0.508-mm (0.020-in.) depth of cut used for all the tests to date. In this way, the rubbing interface between the cutter and the rock can be lubricated, reducing the frictional forces and consequently reducing frictionally generated heat.

It should be noted that not only were the cutting forces reduced by the use of the fluid but also the thrust forces normal to the rock surface were reduced. The thrust force is, to a large degree, a measure of the force necessary for the cutter to penetrate the rock. Reduced friction between rock and cutter will lower the required thrust force to some extent, but speculation suggests that the marked reduction seen in these experiments may indicate that the fluid is reducing the strength of the Nugget sandstone. Much research has been carried out on the effects of fluids on rock properties, and certain fluid compositions have been shown to have strength-reducing effects. Generally, however, the kinetics involved are too slow to benefit rock drilling performance significantly. It is not the objective of this program to investigate these phenomena, but certain experiments are suggested that may help to sort out the relative contributions of cooling, lubrication, and the effects of surface-active fluids. These experiments are the following:

1. Repeating selected tests using nonporous rock such as marble or granite.
2. Increasing the depth of cut for Nugget sandstone to the point beyond which the fluid penetrates the rock, if this depth is reasonable.
3. Utilizing a water-base coolant containing no lubricating constituents. The planned tests with drilling muds may serve this purpose.
4. Performing friction measurements independent of rock cutting tests with the rock types previously used and with selected fluids, including those fluids already chosen for investigation within this program.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ——— ACTIVITY PERIOD ○ PLANNED START ▼ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▼ COMPLETED

4.4 Wellbore Inertial Navigation System (WINS)

Sandia National Laboratories
Technical Consultant: S. Kohler (505) 846-0421

Project Objective

The objective of this project is to provide a system that is capable of making an accurate positional survey of a geothermal wellbore.

Project Status

This project was initiated last quarter. The fabrication of the system hardware and the testing of the supporting software are proceeding on schedule. The first field test of WINS is planned for August 1981 at the Nevada Test Site.

Quarterly Progress

Technology that was developed as part of the Sandia work in fielding inertial navigation systems for flight vehicles is being used in this program. The downhole tool is 0.1 meter (0.33 foot) in diameter and is approximately 6.1 meters (20 feet) long, including the battery pack. A single-gimbaled configuration with two strapdown axes requires two gyros for the attitude determination of three accelerometers that provide the velocity and position output. Improved accuracy will be obtained by the use of a Kalman filtering formulation for estimating the inertial system errors and updating the navigator.

All drawings for the mechanical system, the electronic schematics, and the printed circuit board layouts have been completed. The present design work is on the tool-to-wireline electronic interface for the input/output and the line driver. All of the machining for two complete models has been completed. In addition, the battery pack has been fabricated but not yet tested. The pressure barrel, including a shock nose, cable head, and bow centralizers, has been received and assembled. The electronic assembly is complete for the power supply and analog/frequency converters; additional circuit boards are nearing completion.

Some insight into tool motion, resonance, and stabilization is being gained from ongoing shallow-hole, i.e., 36-meter (120-foot), tests. Only rate gyros are mounted in the tool for spectrum analysis.

The development and testing of software programs continued during this quarter. Also, research was directed at the problem of transmitting at high data rates on a seven-conductor wireline. Two modulation techniques, frequency and current, are being evaluated.

An industry briefing on the system development was presented to Exxon during this reporting period.

5. DRILLING FLUIDS

Improved drilling fluids are needed to reduce the cost of drilling geothermal wells. The corrosive conditions, high temperatures, and fractured formations typical of geothermal resource areas impose severe operating requirements on drilling fluids. Under these conditions, the physical and chemical behavior of drilling fluids is not currently well understood; thus, basic investigations are needed to develop an understanding of the behavior of drilling fluids in the geothermal environment in order to formulate more cost effective fluids. The approach to developing improved drilling fluids includes basic research into the morphology of clay particles, laboratory investigation of the properties of drilling fluids at high temperature and pressure, development of aqueous foam drilling fluids, development and field demonstration of the generation of inert gas drilling fluids, and development and field testing of high-temperature drilling muds. Projects are progressing with the objectives of determining the high-temperature/high-pressure rheological properties of drilling muds, of gaining a fundamental understanding of the morphology of clay particles under the influences of high temperature and various chemical compounds, and of identifying and developing foam drilling fluids capable of operating in temperature environments to 310°C (590°F) and having chemical and foaming stability and anticorrosive and antioxidant properties. The status and progress of these activities are described within this section.

During the first quarter of FY81, drill pipe corrosion field tests were run with air and nitrogen being used alternately as the principal component of the drilling fluid. A significant reduction in drill pipe corrosion was observed when nitrogen was used.

The demonstration of a technique of nitrogen generation from diesel engine exhaust using a catalyst and the field testing of a high-temperature drilling mud, HTM-1, were successfully completed in FY80.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ————— ACTIVITY PERIOD ○ PLANNED START ▼ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▼ COMPLETED

5.1 Aqueous Foam Drilling Fluids for Geothermal Applications

Sandia National Laboratories

Technical Consultants: P. Rand (505) 844-7953
A. Kraynik (505) 844-0780
L. Mondy (505) 844-0780
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Project Objective

This project will identify and develop aqueous foams for use in geothermal applications. The foams will be capable of operating in elevated temperature environments to 310°C (590°F) and will exhibit chemical and foaming stability and anticorrosive and antioxidant properties.

Project Status

An initial report was issued defining the basic problems to be encountered, the various solutions thought to be obtainable, and an overall project plan. The initial surfactant screening has been completed. The testing of surfactants at 260°C (500°F) in various chemical environments has been completed except for any new surfactants that may be submitted in the future. Testing also has been conducted at 310°C (590°F). The evaluation of surfactants after exposure to 260°C (500°F) and 310°C (590°F) in various aqueous environments is essentially complete. A journal article and a report are being prepared on this work.

During the first quarter of FY81, a rheology literature study was completed, a simple heat transfer model was developed, and tensiometer coalescence studies were initiated.

Procedures have been developed to generate and evaluate foams in a high-temperature/high-pressure environment in a new autoclave. Some preliminary tests were run between 50° and 200°C (122° and 392°F) during this reporting period.

Additional testing facilities are being constructed. These facilities will be used to study the rheological and heat transfer characteristics of the high-temperature/high-pressure foams.

Quarterly Progress

High-Temperature Stability Tests -- Aqueous foams were generated in an autoclave at pressures as high as 5.5 MPa (800 psi) and temperatures as high as 200°C (392°F) in a preliminary investigation. Only the foam volume change or subsidence was measured. The subsidence was strongly temperature dependent as evidenced by the times to 50% subsidence of 3.2 minutes at 200°C (392°F), 8.0 minutes at 150°C (302°F), and 26.0 minutes at 100°C

(212°F). After these preliminary tests, the foam generating system was calibrated to allow the generation of foams with controlled liquid volume fractions at pressure and temperature. Considerable time was also spent refining the technique used to measure foam liquid drainage in the autoclave. These tests led to the discovery that increasing the pressure caused a large increase in the liquid drainage time. This effect was unexpected and could have great technological importance because almost all foam drilling and cleanout procedures use a pressurized foam. The current data, obtained with an alpha olefin sulfonate surfactant/nitrogen gas foam show a sevenfold increase in liquid drainage time over the 0.1 to 1.1 MPa (1 to 11 atmospheres) pressure range. Tests will be run with amphoteric, cationic, and nonionic surfactants and with other gases to determine if this effect is present in other systems. Tests at elevated temperature will continue as soon as the effects of pressure on the alpha olefin sulfonate surfactant are defined.

Heat Transfer Modeling -- A solution of the energy equation for foam circulating in a wellbore has been developed and was reported earlier. This simple model has been used to perform a parameter study to identify those parameters that have the greatest influence on the maximum foam temperature. Under normal conditions, the maximum foam temperature occurs in the annulus near the bottom of the hole. The most important parameter identified in the parameter study was the overall heat transfer coefficient between the upward-flowing foam in the annulus and the downward-flowing foam in the pipe. This overall heat transfer coefficient is composed of two different convective heat transfer coefficients, one on the inside surface of the drill pipe and one on the outside surface of the drill pipe. It is felt that these two heat transfer coefficients are influenced by the presence of tool joints located at 9.1-meter (30-foot) intervals. Calculations have indicated that if the flow separates on the downstream side of the tool joint, the maximum foam temperature can be considerably higher than if the pipe walls were perfectly smooth.

A counter-flow heat-exchanger-type experiment has been designed to study the effect of tool joints on foam heat transfer. The foam will flow through an inner tube having an inner diameter of 2.54 cm (1-in.) and a length of 3.1 meters (10 feet). The foam will be heated by hot water circulating around the exterior of the tube. The temperature increase of the foam, temperature decrease of the hot water, and mass flow rates of foam and hot water will be measured. Tests will be conducted with and without the simulated tool joints in order to determine the enhanced heat transfer due to the presence of the tool joints. The pressure drop along the length of the test section will also be measured.

Rheology Experiments -- Plans for the series of aqueous foam flow experiments required an estimate of the equipment and pipe sizes needed to match the shear rates expected during geothermal drilling. An interactive computer program was written that uses the algorithms developed by Chevron Oil Field Research Company to give quick estimates of shear rate, shear stress at the wall, and pressure drop experienced by a foam flowing through a tube or annulus.

Thermal Conductivity -- From the analysis of the effects of heat transfer on the circulating temperatures of aqueous foam during drilling in

geothermal formations, it was concluded that the predominant variables that affect the magnitude of the temperatures are the flow rate of the foam, the effective thermal conductivity of the foam, and convective heat transfer phenomena such as the flow regime and the separation of boundary layers at tool joints. It was noted that a fundamental lack of knowledge exists in the areas of foam rheology, convective heat transfer in foam-like fluids, and thermal property characterization. With the goals of increasing the understanding of aqueous foam behavior in wellbores and of providing a data base for the development of a numerical simulation capability, studies are presently being conducted in each of these three areas. A description of the activity in the measurement of the effective thermal conductivity of aqueous foam follows.

• Theory

The fact that foam is a cellular composition of liquid in the continuous phase and gas in the discontinuous phase makes the characterization of its thermal properties an exercise in finding the proper weighting of the constituent properties. In the case of thermal conductivity, the effective conductivity of the foam is found to be a function only of the foam liquid-volume fraction and the liquid and gas conductivities. Several models for the effective conductivity of foam, which are based on well-known theories of heat conduction through heterogeneous materials, are being investigated. The correlations are plotted in Figure 5-1 along with the limiting cases of parallel and series ordering of the phases.

• Experiments

A number of investigators have measured the thermal conductivities of rigid plastic or polymeric foams over a range of temperatures and heat fluxes. No such data exist for aqueous foams, although several investigators have measured the analogous electrical conductivity. In general, consistent agreement has been found with models similar to those proposed for the thermal conductivity, but, in most cases, the discontinuous gas phase has been treated as a nonconducting component.

Preliminary measurements of the thermal conductivity of various foam samples were made with a thermal conductivity probe in Sandia's Thermophysical Properties Laboratory in order to determine the suitability of this technique. Basically, the thermal conductivity of a sample is determined indirectly by measuring the temperature-time history of the heated cylindrical probe in a representative volume of material. The probe used in these preliminary measurements was constructed in the laboratory and consists of a 1.57-mm (0.062-in.) diameter commercial heater to which has been attached a 1.02-mm (0.040-in.) diameter thermocouple (Figure 5-2). No attempt was made in these trial runs to optimize either the heater power or the test duration. The probe was inserted in 470-ml (28.8-in.³) samples of foam, and the probe power was set at values ranging from 2.6 w/m to 5.85 w/m. In all cases, the aqueous foam was an Edgewood High-Stability Foam formulation consisting of National High-Expansion Foam Surfactant, glycerine, and water with nitrogen as the gaseous phase.

Representative probe response is shown in Figures 5-3, 5-4, and 5-5 for foams with liquid volume fractions of 0.049, 0.074, and 0.102, respectively. In all cases, the probe power was 2.6 w/m. Qualitatively, the

Figure 5-1. Effective Thermal Conductivity versus Liquid Volume Fraction

Figure 5-2. Sandia National Laboratories Thermal Conductivity Probe

Figure 5-3. Representative Temperature Probe Response versus Log Time

Figure 5-4. Representative Temperature Probe Response versus Log Time

Figure 5-5. Representative Temperature Probe Response versus Log Time

probe response was as expected. The early time behavior is characterized by a finite thermal capacitance of the probe that eventually diminishes in effect, and the temperature approaches a log-linear behavior. From the linear region, the thermal conductivity, k , was calculated as

$$k = \frac{\dot{Q}/l}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \quad (1)$$

where T is temperature at the probe surface, t is time, l is heated length, and $\dot{Q}$ is quantity of heat.

The values of the effective conductivity measured are shown in Figure 5-6 along with the theoretical values for parallel ordering. Theoretically, the parallel ordering should yield the highest value of conductivity achievable for a heterogeneous mixture. In all cases, the measured values for foam exceed this limit.

Two explanations are offered for the seemingly high measured values of the conductivity. The most serious experimental difficulty in foam of this type is to minimize the contribution to heat transfer by means other than conduction. It is inevitable that the heated probe will induce convection circulation in the gaseous phase contained within individual bubbles. More importantly, the fluid contained in the films and plateau borders of the foam structure will migrate under the influence of finite temperature gradients. The liquid migration will become more pronounced as the temperature increases and so too will the departure from the thermal conduction response. Also, the test duration must be limited to short times in which liquid drainage in the gravity field will not significantly enhance heat transport.

In the measurements made to date, the data taken beyond times on the order of four minutes are probably not valid. Not only are the temperature increases too large to insure pure conduction heat transfer, but also the effects of drainage most likely become significant at the longer times. The log-linear response regime is susceptible to misinterpretation due to the reasons noted above. The values of conductivity calculated from the linear region can thus easily be outside the domain of experimental uncertainty.

Even with these probable errors in measurement, it is seen from Figure 5-6 that the measured values increase monotonically with increasing foam density. Furthermore, those data that show the greatest scatter were taken at the highest heat fluxes, again pointing to the effects of temperature-induced fluid motion. In addition, the probe response did not demonstrate any significant departure from expected behavior except for very long times. Based on these tests, it is assumed that the probe technique will suit the measurement of conductivity in aqueous foam. Further tests are planned.

Figure 5-6. Preliminary Thermal Conductivity Data

• Experimental Plans

A 0.51-mm (0.02-in.) diameter commercial thermal conductivity probe has recently been acquired, and a 1.52-mm (0.06-in.) probe of the same manufacture is on order. These commercial probes have the thermocouple mounted internally so that the probe is of a single diameter over its entire length. It is felt that these probes will provide a more accurate determination of the thermal conductivity. A typical cross section of one of these probes is shown in Figure 5-7.

A laboratory-scale foam generating system has been built in order to generate and flow aqueous foam directly into a test cell containing the conductivity probe. A schematic of the system is shown in Figure 5-8. The generator consists of a 9.5-mm (3/8-in.) inner diameter, 20.3-cm (8-in.) long stainless steel tube packed with coarse brass wool. From an evaluation of the quality of the foam generated, it was found that a range of densities can be produced from approximately 40 kg/m³ to 300 kg/m³ (2.5 lb/ft³ to 18.7 lb/ft³); the average bubble diameters observed under magnification ranged from 0.127 mm to 0.381 mm (0.005 in. to 0.015 in.). Lighter foams can be generated by increasing the tube packing density.

At the present time, measurements of the conductivity are planned only at atmospheric pressure and temperature. From the experience gained in the preliminary tests, it was decided that probe powers less than one watt per meter will be used and that maximum temperature increases will be kept below 5°C (9°F). It is doubtful that the test duration will allow the temperatures to reach the log-linear regime. For this reason, the thermal conductivity will have to be calculated from an examination of the early nonlinear temperature response. Parameter estimation programs have recently been written to enable these calculations to be made. The measurements at standard conditions are expected to be completed in the next reporting period.

Figure 5-7. Thermal Conductivity Probe, Model CS-48, Custom Scientific Instruments

Figure 5-8. Thermal Conductivity Apparatus

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>NITROGEN/DRILL PIPE CORROSION TEST</u>													
PRETEST DRILL PIPE INSPECTION													
INSTRUMENTATION CHECKOUT													
BACA 20 WELL													
BACA 21 WELL													
FIELD TEST AT BACA 22 WELL													
POST-TEST DRILL PIPE INSPECTION													
FINAL REPORT													

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

TENTATIVE

5.2 Nitrogen/Drill Pipe Corrosion Test

Sandia National Laboratories
Technical Consultant: B. Caskey (505) 844-8835

Project Objective

The purpose of this test is to obtain data on the rate at which drill pipe corrosion occurs when air is used as the principal component of the drilling fluid and, alternatively, when an inert gas, nitrogen, is used as the principal component. These data, when combined with onsite inert gas generation data, will form the basis for an economic study to evaluate the reduction of drilling costs through the use of inert gas drilling fluids.

Project Status

The corrosion test was conducted on 6-16 November 1980 during the drilling of the Baca Well No. 22. Data reduction has been completed. Data analyses and evaluations are under way. The posttest drill pipe inspection was completed.

The final report is being prepared; however, the final compilation of the data has been delayed because the analyses of the liquid samples have not been completed.

Quarterly Progress

The posttest drill pipe inspection was performed by PA, Incorporated, at their yard in Odessa, Texas, on 13 and 14 January 1981. A preliminary data analysis using simple statistics did not show any significant change in the drill pipe during the test. The wall thickness change of about 76 μm (3 mils) that was expected during air drilling was smaller than the resolution capability of the measurement technique, which is approximately 127 μm (5 mils). It was assumed that PA could measure about a 25- μm (1-mil) change, but the pipe surface roughness contributed approximately another 102 μm (4 mils). Sandia National Laboratories statisticians are performing more sophisticated analyses of the data. Their results are not presently available.

The gas samples collected during the test have been analyzed, but the liquid sample analyses have not been completed. The analysis contract that was to be used for these samples has expired. Therefore, either the work will be done at Sandia or a new contract will be negotiated. The analysis plan is being changed to specify only the critical constituents so that timely analyses can proceed. The final report will be published as soon as the results of the analyses are available.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ————— ACTIVITY PERIOD ○ PLANNED START ▼ PLANNED COMPLETION
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5.3 Development of High-Temperature/High-Pressure Drilling Mud Research Instrumentation

Contractor: NL Baroid
Principal Investigator: K. L. Walter (713) 527-1100
Contract Period: 1 April 1978 to 31 March 1981
Contract Number: DE-AC04-77ET27144
Technical Consultant: C. Carson (505) 844-6968

Project Objective

This project will result in the fabrication of a drilling-mud testing instrument capable of measuring fluid properties under down hole conditions of up to 371°C (700°F) and 138 MPa (20,000 psi).

Project Status

The cooling plate was received by NL Baroid in perfect condition after a 138-MPa (20,000-psi) pressure test. The construction of the geothermal drilling fluid test system (GDFTS) building has been approved and will begin in April 1981. The microcomputer software was tested. As a consequence, a few software errors were corrected, and improvements are being made.

Except for the corrosion probes, which have been redesigned, the fabrication of the remaining instrumentation has been completed, and a checkout of this instrumentation was initiated.

Application is being made to DOE for additional funding and a time extension for this project.

Quarterly Progress

The cooling plate was received by NL Baroid after a pressure test to 138 MPa (20,000 psi) that was performed by National Forge Co., Irvine, Pa. The plate seemed to be in perfect condition. The ceramic diffusion shield and insulator plates were machined to match with holes in the cooling plate. With the cooling plate as a base, much of the system hardware can be assembled. A few minor fit problems were corrected, and a few remain.

Portions of the rheometer, filter, density sensor, bucket lift, dispersator, temperature sensor, and gas-cleaning systems have been operated and calibrated. A number of minor problems were resolved, and a few remain. Potential problems with the rheometer measurements of the gel strength and with the fit and flexibility of the filter belt are being addressed. Parts were ordered for the new corrosion probe design, the bottom thermocouple feed-through, and the pressure control valves.

Two circumstances are delaying the progress of this program. Differential pressure tests cannot be performed on the filter until it is installed in the pressure vessel in the new GDFTS building. Secondly, GDFTS building appropriations are being delayed by planning and cost estimates that are being made for a contiguous laboratory. Current plans call for a 6-month construction period with construction beginning in April 1981. The pressure vessel should be completed and hydrostatically tested in May.

In a simulation of the controlling of mud temperature, the microcomputer software operated one of the 3-kW mud heaters, and temperature readings were fed back by the resistance thermometer device (RTD). The computer settings were successfully adjusted to provide the satisfactory temperature control of water in a range of about 66° to 93°C (150° to 200°F) in the mud bucket. The software contains time-proportioning proportional, integral, and derivative control laws.

The microcomputer and all its peripheral equipment were moved to a central laboratory with the GDFTS system. Systran Corporation, Dayton, Ohio, then began demonstrating each of the software elements designed during the subcontract period. The system performed well during the test, which involved coupling the microcomputer with the cathode-ray tube/type-writer console, the high-speed printer, most of the GDFTS hardware, the uninterruptible power supply, a load to simulate sensor inputs, and relays for output signal detection. Several normal test sequences were simulated, and the data were logged. Also simulated were several possible malfunctions that result in warnings, alarms, or, sometimes, system shutdown.

Systran conducted a follow-up test to the software acceptance test, and the few bugs found in the software were corrected. Additional operating improvements were discovered. Among these were needs for a secondary, redundant vessel-pressure sensor, an audible alarm, freeze mode setpoint retention, stepper motor ramping, and a pause before final filtrate weighing. NL Baroid is working on the software and hardware to satisfy the additional needs.

Systran's contract work has been completed. However, the company will be supplying a software maintenance manual. NL Baroid will be writing the software operator's manual and the hardware operating manual.

W. Clements and K. Walter of NL Baroid attended the International Conference on Geothermal Drilling and Completion Technology in Albuquerque, New Mexico, in January 1981. At the conference, current progress and future plans for this project were reviewed informally with DOE and Sandia personnel.

The DOE Contract Administrator notified NL Baroid on 16 February 1981 that the company had exceeded the contract budget with their January billing, which was triple the normal billing because of large payments to National Forge and Systran. An additional amount of DOE funding is being requested. The request includes an explanation of overruns and an estimate of additional funding required for project completion. The availability of additional funding is uncertain. If the request is not granted, the details regarding the termination of the contract will be negotiated.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>DRILLING MUD CHEMISTRY:</u> <u>TEXAS TECH UNIV.</u>													SEP 81
THERMAL EFFECTS ON THIXOTROPIC PROPERTIES ATTAPULGITE SEPIOLITE SAPONITE BENTONITE													

LEGEND: ——— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

5.4 Basic Understanding of Chemical and Elevated Temperature Effects on Clay-Based Drilling Fluids

Contractor: Texas Tech University
Principal Investigator: N. Güven (806) 742-3110
Contract Period: 15 July 1979 to 1 September 1981
Contract Number: 13-5104 (Sandia)
Technical Consultant: C. Carson (505) 844-6477

Project Objective

This project will result in a fundamental understanding of clay particle morphology under the influence both of various chemical species and elevated temperatures similar to the conditions encountered during geothermal drilling activities. On the basis of this understanding, clay-based, geothermal drilling-fluid systems, complete with the additives dictated by downhole conditions, will be designed for use in geothermal drilling.

Project Status

The Texas Tech University Clay and Drilling Fluids Laboratories were remodeled to accommodate the project. The project investigations were initiated in July 1979. X-ray and microscopic studies of the effects of various salts and elevated temperatures on clay morphology are continuing.

Quarterly Progress

Scanning Electron Microscopic Observations on Sandstone Cores from East Mesa, Imperial Valley, California -- Cores from Republic Geothermal, Inc., Well 70-30rd, East Mesa, Imperial Valley, California, were examined after they were subjected to tests by Terra Tek.¹ These tests were aimed at assessing the possible formation damage caused by the HTM-1 drilling fluids. The virgin core was designated as 1-64 and the test cores as 2-64 and 2-76. Enniss et al. reported in Reference 1 that core 2-76 lost a great deal of permeability after 48 hours of stagnation with the HTM-1 drilling fluid at 100°C (212°F), whereas core 2-64, after 12 hours of stagnation time at 200°C (392°F), suffered negligible permeability loss. The virgin core, 1-64, and the other two cores, 2-64 and 2-76, have been examined with X-ray diffraction, SEM,* and EDAX.** Each core was originally 10.2 cm (4 in.) long. The cores were divided into four parts, each one being 2.54 cm (1.0 in.) long. These sections were designated by the letters A, B, C, and D, where A is the section of the core next to the filter cake and D is the opposite end of the core. All four sections were examined separately. The results of the X-ray diffraction analyses on the

* scanning electron microscopy

** energy dispersion analysis of X-rays

bulk samples and on their clay fractions were given in the FY80 Annual Report. The SEM examination of the virgin core was discussed in the first quarterly report for FY81. As explained in these reports, the clays in the virgin core consist of illite/smectite mixed layers and chlorites. The morphological features of these components consist of rosettes of chlorites and flaky illite/smectite mixed layers with hair-like illite laths growing from them. These morphological features strongly suggest that the clays represent diagenetic new formations. Following is a description of the SEM studies conducted on the test cores.

• Test Core 2-64

As in the virgin core, the clays in this test core consist of illite/smectite mixed layers and chlorites. The clay coatings of the sand grains are a little denser than they are in the virgin core and lack the hairy and, therefore, voluminous illite laths, as shown in Figure 5-9. The figure is obtained from the cake end, section A, of the core, where chlorite rosettes and massive flaky illite/smectite mixed layers with a honeycomb-like microstructure occur as pore linings. Similar features of clay minerals are also shown at a higher magnification in Figure 5-10, which illustrates part of the D section of test core 2-64. The major difference from the clays in the virgin core can be seen in Figure 5-11, where the association of hairy illite with flaky illite/smectite mixed layers is clearly visible.

The very surface of section A of test core 2-64, next to the filter cake, also has been examined, and similar clays are observed. No sepiolite or bentonite particle has been found on the surface or within the core. Thus, no sepiolite or bentonite migration from the drilling mud into the core has been observed.

• Test Core 2-76

The relative amounts of clay minerals in this core show a slight trend toward an increase in illite/smectite mixed layers and in chlorite from the D section towards the A section. This pattern suggests that these clay minerals may move in a direction from the D section towards the A section with formation water during the backflow. However, the same type of clay minerals, i.e., illite/smectite mixed layers and chlorites, predominate and have morphological features similar to those described previously for test core 2-64. Again, no sepiolite or bentonite particle is found, even at the surface of the core next to the mud chamber. Thus, the backflow seems to have washed out all the clays that were deposited by the drilling mud. Furthermore, the permeability loss is most likely related to the migration of water-sensitive clays such as chlorite, illite/smectite mixed layers, and hairy illite in this core rather than to the migration of the clays in the HTM-1 mud.

X-Ray Diffraction Data on Drilling Fluids Subjected to Hydrothermal Treatments at Very High Temperatures -- Each of three samples of attapulgite mixed with magnesium, sodium, or potassium chloride (5 grams [0.18 ounce] of clay and 1 gram [0.035 ounce] of salt per 100 cm³ [6.1 in.³] of water) was heated in the autoclave at 371°C (700°F) and at 427°C (800°F). These samples were analyzed by X-ray diffraction methods. The interplanar spacing measurements, d-values, resulting from the analyses are shown in Table 5-1.

Figure 5-9. Clays in the Pores of Test Core 2-64A. Rosettes of chlorites and honeycombs of flaky illite/smectite mixed layers occur as pore linings. Mag: 500X.

Figure 5-10. A Higher Magnification View of the Predominant Clays in Test Core 2-64. Note the rosettes of authigenic chlorites and honeycomb-like aggregates of flaky illite/smectite mixed layers. The latter display very few hairy illite laths growing from them, in contrast to Figure 5-11. Mag: 200X.

**Figure 5-11. Typical Hairy Illites Growing from Flaky Illite/
Smectite Mixed Layers in the Virgin Core, Section C.
Mag: 200X.**

Table 5-1

Interplanar Spacing Measurements, d-Values, Obtained by the X-Ray Diffraction
of the Drilling Fluids after Hydrothermal Treatment at 371°C (700°F)
and at 427°C (800°F)

Fluid Designation	Smectite	Illite	Illite/ Smectite	Quartz	Feldspar	Tremolite/ Talc
Attapulgate/KCl/371°C (700°F)						
Before Glycolation	NP	10.89 Å*	P	3.35 Å	3.15 Å	NP
After Glycolation	17.1 Å*	10.09 Å	NP	NP	NP	NP
Attapulgate/KCl/427°C (800°F)						
Before Glycolation	NP	10.53 Å*	P	3.34 Å	3.15 Å	NP
After Glycolation	P	10.05 Å*	NP	NP	NP	NP
Attapulgate/MgCl ₂ /371°C (700°F)						
Before Glycolation	12.49 Å*	NP	NP	NP	NP	NP
After Glycolation	16.9 Å*	NP	NP	3.34 Å	3.25 Å	NP
Attapulgate/MgCl ₂ /427°C (800°F)						
Before Glycolation	14.98 Å*	NP	NP	3.35 Å	NP	NP
After Glycolation	NP	NP	NP	NP	NP	NP
Attapulgate/NaCl/371°C (700°F)						
Before Glycolation	12.70 Å (BP)*	NP	NP	3.35 Å	NP	NP
After Glycolation	17.0 Å*	NP	NP	NP	NP	NP
Attapulgate/NaCl/427°C (800°F)						
Before Glycolation	13.27 Å (BP)*	NP	NP	3.35 Å	3.21 Å	NP
After Glycolation	17.0 Å*	NP	NP	NP	NP	NP
Sepiolite/CaCl ₂ /371°C (700°F)						
Before Glycolation	15.24 Å*	NP		3.35 Å	3.18 Å	8.57 Å
After Glycolation	17.1 Å*	NP		NP	NP	NP
Sepiolite/CaCl ₂ /427°C (800°F)						
Before Glycolation	15.34 Å*	NP		3.34 Å	3.21, 3.14 Å	8.64 Å
After Glycolation	17.0 Å*	NP		NP	NP	9.03 Å

NOTES:

* represents the strongest reflection on the pattern.

NP indicates that the substance was not present.

P indicates that the substance was present.

BP indicates broad peak.

In general, the attapulgite changes into smectite, except that illite forms in the presence of KCl. The interlayer cations of the smectite are determined by the salts added before treatment and by the original attapulgite composition. Besides the formation of illites and smectites, there are probably some feldspars formed at 427°C (800°F). Further investigations by electron microscopy will yield more detailed data on the changes exhibited by attapulgite/cation solutions exposed to high temperatures. The following discussions are basically derived from the X-ray diffraction data.

- Attapulgite/KCl System

The treatment of attapulgite with KCl at 371° and 427°C (700° and 800°F) basically results in the formation of illite, smectite, and illite/smectite mixed layer clay minerals. However, there is a significant difference between the amount of illite and smectite being formed at 371°C (700°F) and 427°C (800°F). At 371°C (700°F), the X-ray diffraction data show a reflection with a d-value of 10.89 Å, which separates into a strong smectite phase at 17.1 Å and a weak illite phase at 10.09 Å after the glycolation. There is probably a small amount of illite/smectite mixed layer formed, as interpreted from the X-ray diffraction data. The diffraction pattern gives a 10.53-Å peak at 427°C (800°F). After the glycolation, the main peak remaining is an illite reflection at 10.05 Å, with a weak and broad peak at about 17 Å. There is still a small amount of smectite unaltered. Apparently, the illite formation is favored by a higher temperature, and the amount of smectite is drastically decreased at 427°C (800°F). If the smectite to illite transformation is a simple process, e.g., potassium fixation, then the illite formed should be high in aluminum and low in magnesium as compared with the smectite.

- Attapulgite/MgCl₂ System

The smectite formed in the system gives a basal spacing of 12.5 Å at 371°C (700°F) and a basal spacing of 14.98 Å at 427°C (800°F). The difference between the two smectites could mean that the magnesium ions in the smectite at 371°C (700°F) partially occupy the potential interlayer positions. With the increasing temperature, these ions gradually move to available interlayer cation positions. The smectites are aluminum and magnesium rich, as are those observed in the distilled water system, and the smectites expand to 17 Å after the glycolation.

- Attapulgite/NaCl System

Smectites formed in this system are expected to have sodium as the interlayer cation. The observed basal spacings of the smectites are, in fact, close to those of the ideal Na-smectites. However, the d-values, 12.7 Å and 13.3 Å, are greater than the d-value of an ideal Na-smectite. This discrepancy, again, is probably caused by structural variations so that a few magnesium ions are still distributed in the structure as interlayer cations, thus broadening the reflections and shifting the peak positions. After the glycolation, the smectites yield a basal spacing of 17 Å.

- Sepiolite/CaCl₂ System

Two sepiolite samples in a CaCl₂ system were also prepared and heated to 371° and 427°C (700° and 800°F). Basically, the diffraction data are similar to those observed in the distilled water system. However, the

smectite formed seems to be a Ca-smectite with d-values of 15.24 Å and 15.34 Å at 371° and 427°C (700° and 800°F), respectively. It is interesting that even with the presence of CaCl_2 the sepiolite still did not change completely into talc and tremolite.

Rheological Measurements of the Sepiolite-Based Drilling Fluids Subjected to Hydrothermal Treatments -- The sepiolite-based drilling fluids were prepared and tested as follows. Five-percent clay to water suspensions of sepiolite were mixed in a Hamilton Beach blender for 15 minutes; 500 cm³ (30.5 in.³) of the mud was then transferred to an autoclave cell and heated to a desired temperature and pressure. Following this, the rheologic properties of the muds were measured by means of the Fann 50C high-pressure/high-temperature viscometer, the Fann 35A viscometer, the Baroid high-pressure/high-temperature filter press, the Baroid standard filter press, and the Baroid 600-20 pH meter. Subsequently, chlorides and hydroxides of sodium, calcium, potassium, or magnesium were added to each clay suspension so that a 1% salt or hydroxide concentration was obtained in these suspensions. These systems were also heated in the autoclave and their rheological properties measured. These tests have been performed at 21°, 204°, 260°, 316°, 371°, and 444°C (70°, 400°, 500°, 600°, 700°, and 800°F). The rheological measurements are listed in Table 5-2.

The high-temperature rheology measurements were obtained from a Fann 50C viscometer. These measurements are represented by the rheograms in Figures 5-12, 5-13, and 5-14. Figure 5-12 gives the rheogram of the drilling mud based on pure sepiolite at room temperature and after the hydrothermal treatment at 204°C (400°F). Figure 5-13 represents the rheograms of the same fluid after the hydrothermal treatments at 371° and 444°C (700° and 800°F). Figure 5-14 gives the rheograms of the mud consisting of sepiolite and MgCl_2 at temperatures of 204°, 260°, and 316°C (400°, 500°, and 600°F).

Presently, the results are being interpreted in terms of the high-temperature chemical reactions that occurred in the mud under hydrothermal conditions.

Reference

1. D. O. Enniss et al, "Drilling Fluid/Formation Interaction at Simulated In Situ Geothermal Conditions," report submitted to Sandia Laboratories in November 1979.

Table 5-2

Rheological Data on Sepiolite Mud as Obtained from the Measurements with the FANN 35A Viscometer

Component Added to the Sepiolite/H ₂ O Suspension	Temperature °C (°F)	Plastic Viscosity ^a Pa·s (lb/ft·h)	Yield Point Pa (lb/ft ²)	Gel Strength Pa (lb/ft ²)	pH	Room Temp. Rate of Filtration ^b cm ³ /min (in. ³ /min)	HP-HT ^c Rate of Filtration ^b cm ³ /min (in. ³ /min)	Room Temp. Cake Thickness cm (in.)	HP-HT ^c Cake Thickness cm (in.)
CaCl ₂	371 (700)	0.004 (9.7)	1.9 (0.04)	0.41 (0.0086)	7.0	42.7 (2.61)	17.1 (1.04)	0.71 (0.28)	0.32 (0.13)
CaCl ₂	444 (800)	0.005 (12.1)	7.7 (0.16)	0.36 (0.0075)	6.0	70.0 (4.27)	20.3 (1.24)	0.79 (0.31)	0.56 (0.22)
MgCl ₂	316 (600)	0.008 (19.4)	6.2 (0.13)	0.25 (0.0053)	6.2	12.0 (0.73)	4.5 (0.27)	1.35 (0.53)	2.54 (1.00)
MgCl ₂	260 (500)	0.011 (26.6)	5.3 (0.11)	0.33 (0.0069)	5.8	13.3 (0.81)	3.7 (0.23)	1.27 (0.50)	2.38 (0.94)
MgCl ₂	204 (400)	0.007 (16.9)	1.9 (0.04)	0.14 (0.003)	6.4	26.1 (1.59)	20.0 (1.22)	2.14 (0.84)	2.22 (0.88)
KCl	21 (70)	0.0025 (6.0)	4.1 (0.085)	0.27 (0.0056)	8.7	18.4 (1.12)	16.9 (1.03)	0.48 (0.19)	0.48 (0.19)
NaCl	21 (70)	0.003 (7.3)	4.3 (0.09)	0.26 (0.0054)	8.5	21.3 (1.30)	7.6 (4.64)	0.32 (0.13)	0.48 (0.19)
MgCl ₂	21 (70)	0.0025 (6.0)	3.8 (0.08)	0.40 (0.0083)	7.7	13.3 (0.81)	8.7 (0.53)	0.40 (0.16)	0.40 (0.16)
CaCl ₂	21 (70)	0.003 (7.3)	2.9 (0.06)	0.32 (0.0067)	8.0	17.3 (1.06)	13.3 (0.81)	0.48 (0.19)	0.32 (0.13)

^aPlastic viscosity was determined by taking the difference between the viscosity measured at 600 rpm and the viscosity measured at 300 rpm.^bAmerican Petroleum Institute procedures were used.^cHigh-pressure, high-temperature.

Figure 5-12. Rheograms of Pure Sepiolite Muds as Measured by the Fann 50C Viscometer. Mud No. 1 was prepared at room temperature, and Mud No. 2 was heated in the autoclave for 16 hours at 204°C (400°F).

Figure 5-13. Rheograms of Pure Sepiolite Muds as Measured by the Fann 50C Viscometer. The muds Nos. 3 and 4 were previously heated in the autoclave at 371° and 444°C (700° and 800°F), respectively.

Figure 5-14. Rheograms of Sepiolite/MgCl₂ Muds Nos. 4, 5, and 6, Which Were Heated in the Autoclave at 204°, 260°, and 316°C (400°, 500°, and 600°F), Respectively

6. COMPLETION TECHNOLOGY

Geothermal well costs are strongly dependent on completion techniques. Improperly completed wells can substantially reduce energy production and require additional well drilling or frequent workover. The approach to improved completions is to develop design criteria, completion techniques, and/or hardware that will extend well life and improve production. Projects are presently under way with the objectives of (1) designing a downhole perforator for use in geothermal well completions, (2) defining current problems with completion equipment and recommending potential solutions, and (3) developing a model that will evaluate the cost of current completion technology, the areas needing development, and the cost benefit of new technology. A project to investigate drilling fluid/formation interactions was completed this quarter. The status and progress of these activities are described within this section.

Completed efforts under this element of the Geothermal Drilling and Completion Technology Development Program have resulted in the identification of failure modes for geothermal well casing. Requirements for technology development to reduce the probability of casing failure were also formulated as part of the casing/liner design and cementing study project.

The necessary development was determined, and the requirements were defined for downhole primary cementing tools and for monitoring tools to detect the critical failure modes of a geothermal well completion.

A new technique using high-pressure cavitating jets to remove scale from pipes in geothermal power plants was demonstrated. The possibility of using the system to remove scale from the wellbore in a flowing well was also demonstrated, and the parameters needed for the design of an operational downhole geothermal well cleaning and scale removal system were established. The development of this system was completed in the first quarter of FY81. During a field demonstration, a cavitation descaler tool successfully removed scale at a cleaning rate of $0.957 \text{ m}^2/\text{min}$ ($10.3 \text{ ft}^2/\text{min}$) with an operating pressure of 34 MPa (5,000 psi).

The first phase of a project to investigate the effect on rock permeability of drilling mud invasion has been completed. The evaluation of the laboratory test results for two mud systems indicated that (1) permeability impairment due to drilling fluid formation/interaction is time dependent with significant impairment occurring within 48 hours residence time, (2) permeability impairment is temperature dependent with lower temperature exposures, i.e., 100°C (212°F), resulting in greater impairment than higher temperature exposures, i.e., 200°C (392°F), and (3) both temperature and time dependence vary with drilling fluid chemistry. A report on the experiments will be published separately.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE	
<u>HIGH-TEMPERATURE PERFORATOR</u>													SEP 81	
STUDY OF OFF-THE-SHELF PERFORATORS	▼													
STUDY OF MDF IGNITION SYSTEMS	●—————▽													
STUDY OF HIGH-TEMPERATURE DETONATORS	●—————▽												SEP 81	

LEGEND: ————— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

6.1 High-Temperature Perforator

Sandia National Laboratories
Technical Consultant: W. Leslie (505) 844-3267

Project Objective

The objective of this project is to determine the feasibility of designing an explosive perforator that is capable of functioning at and after exposure to temperatures of 250° to 300°C (482° to 572°F) for 45 minutes.

Project Status

A variety of conventional explosive perforators was purchased from a commercial supplier. Diagnostic techniques for determining the performance of these perforators were developed. A test chamber was designed and constructed for the heating of perforators at elevated temperatures. After the perforators were heated, the explosive charges were fired into a target and the performance of the perforator evaluated from a study of the target. Trials with the chamber were made in order to establish that it would function as designed. Perforators containing the explosive HNS were heated for 2-hour periods at different temperatures in the special test chamber. The explosive charges were fired into a target and were found to function properly at temperatures up to 250°C (482°F).

Two types of mild detonating fuse (MDF) have been received for use as an initiating train for high-temperature perforators. A study of high-temperature-resistant secondary explosives is in progress in order to select candidate materials for a detonator.

Quarterly Progress

The MDF that contains the explosive HNS-II and is covered with an aluminum jacket has been received. Two types were fabricated: (1) 17 grams per meter (80 grains per foot) with round cross section and (2) 9.6 grams per meter (45 grains per foot) with rectangular cross section. A test has shown that the MDF will initiate a perforator at ambient temperature. No initiation problems are anticipated at 250°C (482°F).

Experiments have been conducted to measure the autoignition temperature of some high-temperature-resistant explosives in order to select a detonator candidate. The powders were pressed into stainless steel housings, sealed, and heated at a rate of 5°C (9°F) per minute until autoignition occurred. A range of autoignition temperatures from 270° to 365°C

(518° to 689°F) was obtained. The 365°C (689°F) temperature is an absolute upper temperature limit for detonating explosives that are presently known.* The 2-hour survival temperatures of some of these same explosives will be studied next quarter. The survival temperature is defined as being lower than the autoignition temperature for each explosive.

* Except for the explosive TACOT, which is slightly higher.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>CAVITATION DESCALING: DAEDALEAN</u>													
DESIGN PARAMETER IDENTIFICATION TESTS	COMPLETED												
SYSTEM DESIGN AND FABRICATION													
CLEANING HEAD	COMPLETED												
TUBING REEL	COMPLETED												
LABORATORY TESTS	COMPLETED												
FIELD DEMONSTRATION
FINAL REPORT

LEGEND: **ACTIVITY PERIOD** **PLANNED START** **PLANNED COMPLETION**
 RESCHEDULED **STARTED** **COMPLETED**

6.2 Cavitation Descaling Technique for Downhole Geothermal Well Cleaning

Contractor: Daedalean Associates, Inc.
Principal Investigators: Dr. A. P. Thiruvengadam
Dr. A. A. Hochrein, Jr. (301) 442-2620
Contract Duration: 14 February 1979 to 28 November 1980
Contract Number: 13-2361 (Sandia)
Technical Consultant: C. Carson (505) 844-6477

Project Objective

The objective of this project was to develop and apply a controlled cavitation technique for downhole geothermal well cleaning and scale removal.

The work in this program was expected to build on technology acquired under a previous DOE contract for the development of a cavitation descaling technique for pipes and tubes in geothermal power plants (Contract Number EG-76-001-2289).

Project Status

The design parameters were identified on 29 and 30 March 1979 at the East Mesa, California, geothermal test facility. The demonstration system design was based on the data obtained from a test conducted on these days. The water-powered hydraulic cleaning head motor to be used in the demonstration system was fabricated. The field demonstration was performed in November 1980. During the demonstration, the cavitation descaler tool successfully removed scale by operating at a pressure of 34 MPa (5,000 psi) and cleaning at a rate of 0.957 m²/min (10.3 ft²/min).

Quarterly Progress

A summary of the results of the cavitation descaler tool demonstration was included in the last quarterly report. The preparation of the final report continued during this reporting period, and the publication of the final report is expected during the next quarter. This project will be deleted from the next quarterly progress report.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>DRILLING FLUID/ FORMATION INTERACTIONS: TERRA TEK</u> FILTRATE CHEMISTRY EFFECTS PARTICLE SIZE EFFECTS FRACTURED FORMATION SIMULATION EAST MESA FORMATION DAMAGE INVESTIGATION FINAL REPORT													

LEGEND: ————— ACTIVITY PERIOD ○ PLANNED START ▼ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▼ COMPLETED

6.3 Drilling Fluid/Formation Interactions

Contractor: Terra Tek, Inc.
Principal Investigator: D. Enniss (801) 584-2400
Contract Period: 10 March 1980 to 31 January 1981
Contract Number: 46-8747 (Sandia)
Technical Consultant: C. Carson (505) 844-6968

Project Objective

The objective of this project was to study, under laboratory conditions, drilling fluid/formation interactions to investigate

1. Permeability alterations due to "salinity-contrast" exposure, as a function of filtrate chemistry, temperature, and exposure rate,
2. Permeability reduction after exposure to drilling muds containing specific-sized bridging particles, as a function of particle size, particle size distribution, and temperature,
3. The best method of simulating formation damage in a fractured formation under laboratory conditions, and
4. The formation damage problems being experienced in the East Mesa known geothermal resource area (KGRA).

Project Status

This project was the second phase of the study of formation damage associated with drilling fluids. Earlier work investigated the effects of the invasion of drilling mud upon the permeability of formations, as a function of varying stagnation times, mud types, and temperature. The Phase I efforts were completed at the close of FY79, and a report was submitted early in FY80. The second phase of the investigation was initiated with laboratory tests to determine any effect in situ brines may have on drilling fluid/formation permeability. These tests were completed in July 1980. Work on the effects of drilling-fluid-entrained particles on formation permeability and on the simulation of formation damage in a fractured formation was completed during this quarterly reporting period. The investigation of East Mesa formation damage was completed at the close of the last quarter.

All work on this project has been completed, and a final report is being prepared. A summary of the report will be included in the next quarterly progress report.

Quarterly Progress

East Mesa Formation Damage -- An analysis of tested East Mesa core material by petrographic microscope, mercury intrusion, and emission spectrometer was reviewed, and the results of the East Mesa investigation were presented at the International Geothermal Drilling and Completion Technology Conference in Albuquerque, New Mexico, in mid-January 1981. In general, the findings of the investigation can be summarized by the statement that the effects of pore fluids in a matrix permeability resource can influence formation productivity significantly. Test results on core samples taken from the East Mesa KGRA lead to the following conclusions:

1. The permeability of East Mesa sandstone is significantly affected by the flow of the synthetic brine having approximately 2,000 ppm, TDS (a low salinity brine).^{*} Permeability reductions of up to 75% are common.
2. The pore fluid alteration of formation clays to a structurally expanded and weakened, frayed-edged condition can allow the velocity and shearing effects of the pore fluid flow to collapse the fragile clay structure, which might occur during production. The clays can disperse within the pore fluid and create obstructions at pore throats, thus reducing permeability.
3. Carbonate dissolution, apparent in the chemical analysis of effluents, may allow the release of previously cemented, fine, interstitial particles. These particles can be transported by the pore fluid and contribute to pore throat blockage.
4. Once the formation matrix has been damaged by exposure to a low-salinity brine, subsequent treatments with high-salinity filtrates produce little or no effect upon permeability.

The results from testing indicate that permeability can be severely and irreversibly impaired. Since the processes affecting permeability are dependent upon the clays present within the pore space, the equilibrium pore fluid, and, possibly, velocity, it is difficult to extrapolate the processes. However, similar processes seem likely to operate in other low-salinity, matrix-dominated sandstone geothermal reservoirs.

Particle Size Effects -- Particle size testing was completed after modifications were made to the mud stirring shaft and the seal system. This task evaluated the effects of 5, 20, and 50 micron (0.2, 0.8, and 2.0 mil) particles as pore-bridging material in a KCl/polymer brine drilling fluid. Tests at 23°, 175°, and 250°C (73°, 347°, and 482°F) were completed with these three different-sized particles and with combinations of these particles at simulated in situ geothermal conditions. Particles added to the KCl/polymer/brine drilling fluid were filtered against a generic sandstone core to evaluate which particle size or combination of sizes were most effective in bridging the pore throats of the rock matrix. The data are being analyzed, and the results will be included in the final report on the project.

^{*}
TDS = total dissolved solids

Fractured Formation Simulation -- Efforts to simulate fractured reservoirs were completed. Work on this task was concentrated in two areas:

1. Design modifications were made to the fluid flow system to accommodate the higher flow rates associated with fractured geothermal systems, and
2. Procedures were carried out to measure the effective fracture width at simulated in situ conditions.

The results of these engineering modifications and designs are being reviewed and will be reported in the final report on the project.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ——— ACTIVITY PERIOD

----- RESCHEDULED

○ PLANNED START

● STARTED

▽ PLANNED COMPLETION

▼ COMPLETED

6.4 Completion Equipment Study

Contractor: Foster-Miller Associates, Inc. (FMA)
Principal Investigator: B. Doherty (617) 890-3200
Contract Period: 1 August 1980 to 1 June 1981
Contract Number: 49-8367 (Sandia)
Technical Consultant: C. Carson (505) 844-6968

Project Objective

The objectives of this project are to describe the problems that exist with the completion equipment and procedures currently in use and to describe the appropriate environmental conditions to which improved equipment and procedures will be subjected. In conjunction with these objectives, recommendations for potential improvements will be made along with an estimate of the economic benefit of each improvement.

Project Status

Work on this project was initiated near the end of FY80. Organizational meetings were held on 28 August 1980 and 11-13 November 1980 to coordinate the work done by FMA and their subcontractor, Completion Technology Company (CTC), with Sandia's overall completion technology program. The pertinent data on completion equipment have been compiled, and the defining of the related problems is continuing. An engineering analysis of the equipment is also in progress.

Quarterly Progress

Emphasis was placed on studying liner design and materials during this quarter. It was concluded that the methods, considerations, and procedures for proper liner design are well documented and available to the operator but are not widely understood or practiced in the field for a number of reasons. It was also concluded that there is little Sandia can do to improve this situation other than to continue its practice of disseminating design information to the end users. In the Imperial Valley, inadequate liner design has not yet surfaced as an acknowledged problem area, probably because of the relative lack of experience and because of the lower temperatures existing at most of the developed areas.

It is understood, according to the literature, that standard API design practices and ratings cannot be directly applied to geothermal wells because of the high temperatures present. The standard practices and ratings are based on assumed values for yield strength and Young's modulus.

But these values may change anywhere from 3 to 18 percent, in K-55 and N-80 casing grades, in the temperature range of 177° to 343°C (350° to 650°F), and so the designers should incorporate these reductions into the liner design. The lower end of the casing string is of particular concern because it can be in compression due to buoyancy effects. As a result of the compression, the onset of yielding due to temperature changes may occur sooner than anticipated in this region if the compressive stresses and reduced yield strengths are ignored. Yielding may be acceptable in a radially unrestrained liner on a single occasion, as the literature seems to suggest. However, the effects on the liner and cement sheath of repeated temperature cycling, and possibly repeated liner yielding, are not well understood and can quite possibly lead to the cracking and failure of the cement sheath and cement sheath/liner bond.

Temperature cycling occurs during well startup when a static fluid column with a thermal gradient starts flowing or during shut-in when the flow is stopped by the injection of cold water. Such procedures, if accomplished rapidly, could generate significant thermal gradients through the liner and cement. The resulting differential thermal expansion or contraction could result in liner or cement sheath damage that could shorten well life by exposing the exterior of the liner to corrosive formation fluids.

Based on field trip observations and literature reviews, it is believed that operators recognize the potential for completion system damage from rapid thermal cycling. However, the shut-in or startup rates used in the field appear to be based on the judgement of the operator rather than on an analytical understanding of the problem. It appears then that this could be a potential area for more detailed investigation. Such an investigation could study the maximum rate of change of temperature that is possible before damage to the cement sheath or liner occurs. An investigation could also be aimed at developing a computer program that a field engineer could use to define startup or shut-in rates, knowing the thermal gradients through the conductive and convective zones and the completion system design.

Most of the published investigations into corrosion resistances of materials for geothermal applications concentrate on materials for surface facilities. The majority of these studies indicate that low carbon steels, 1018 and 1020, are suitable only for thickwall applications in moderate environments where the chloride content is below 20,000 ppm and the pH is greater than 6. In these environments, uniform corrosion appears to be a manageable 51 to 254 $\mu\text{m}/\text{year}$ (2 to 10 mils/year), but localized pitting and crevice corrosion are more severe and less predictable. As a result, a long life for low carbon steel can only be achieved through the use of thickwalls.

The corrosion resistance of liner materials has recently begun to receive attention in the literature. Most field tests of tubular materials have been conducted by the Lawrence Livermore Laboratory (LLL) at the Department of Energy Geothermal Loop Experimental Facility in the Salton Sea geothermal field. In initial testing in early 1979, LLL reconfirmed that J-55 tubing corroded severely in this environment. This 69-day test in Woolsey No. 1 indicated, however, that "API Grades N-80 and C-75 have the potential for providing long life." The results of an 8-month test in

Magamax No. 1 completed in May 1980 by the same investigators from LLL appear to have reversed this conclusion. This work is unpublished because the investigators are still conducting detailed examinations of the specimens. LLL indicated that the N-80 and C-75 tubing samples tested corroded severely in the long-term test and that the potential of these grades for providing long life was now in question.

It appears then that at the Salton Sea field there is a strong need for improved liner materials. This need may spill over into the more moderate environments also. FMA is presently working with the Department of Materials Science and Engineering at the Massachusetts Institute of Technology to determine if improved liner materials are needed, and, if so, what the options are and who is working on these options.

With regard to coupling design, the industry seems satisfied with buttress thread couplings because these have the compressive and tensile strengths required. However, two problems with these couplings could surface in the long run and could influence the need for improved designs. First, crevice corrosion in and around the liner coupling could be severe enough to cause premature failure of the liner connections. Crevice corrosion, as noted previously, has been identified by surface tests as a limiting factor. This was also noted in the report on the corrosion of J-55 tubing in a Salton Sea well. The second potential problem results from the fact that standard buttress thread joints induce high stress levels in the liner and coupling in order to seal. High stress results in high susceptibility to sulfide stress cracking (SSC). Premium joints usually have less stress and fewer crevices in the madeup state because these couplings rely on shoulder or metal-to-metal seals rather than on thread seals. However, these joints usually have upset ends that are thicker than the joint body and that have a different microstructure. These characteristics can make premium joints more susceptible to SSC than would otherwise be the case. Tests have been conducted on couplings that have combined the low-stress features of premium joints with the uniform sections of the buttress thread, and these tests indicate that such couplings are more resistant to SSC than are the available couplings. Additional information on these designs is still being researched.

The analysis of scale removal and control has also been proceeding. Presently, the removal and control techniques published in the literature have been identified, as have the means by which these techniques work, the pros and cons of each, and the documented experience operators have had with them. Scale control is one of the major hurdles in the path of the commercial development of geothermal resources. The control and removal of scale will probably merit additional investigation, but it is not clear at this point whether or not such investigations can benefit more than one well or one field because conditions are so specific for each location.

CTC has been working over the past reporting period to define a minimum set of typical wells. This is a difficult task because of the large number of variables and the extreme variation in these variables. It appears at this point that this set will consist of five typical wells, one well in each of the following locations:

1. The Geysers,
2. Roosevelt Hot Springs,
3. Baca,
4. Salton Sea, and
5. Low-temperature Imperial Valley.

Also, as a result of this compilation and the investigation into sand control, it appears that the majority of the producing formations consist of competent fractured rock. Consequently, there does not appear to be a strong industry need for improved sand control equipment because sand control has not surfaced as a widespread problem. Even in formations where it would be expected, such as the East Mesa, evidence has not been found indicating that sand production is a problem. This problem area will be studied in order to establish whether or not the need to develop improved sand control techniques and equipment exists.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ——— ACTIVITY PERIOD ○ PLANNED START ▽ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▼ COMPLETED

6.5 Completion Technology Life Cycle Cost Model

Contractor: The BDM Corporation
Principal Investigator: A. Mansure (505) 848-5320
Contract Period: 10 November 1980 to 31 October 1981
Contract Number: 46-8777 (Sandia)
Technical Consultant: C. Carson (505) 844-6968

Project Objective

The objective of this project is to provide a model that can be used to evaluate (1) the cost of current completion technology, (2) the areas needing development, and (3) the cost benefit of new technology.

Project Status

The survey of the state of the art of completion technology life cost modeling has been completed. The development of the Life Cycle Cost (LCC) Model was initiated this quarter and is continuing.

Quarterly Progress

The identification of the parameters affecting well completion LCCs is in progress. The open literature concerning both the qualitative and quantitative aspects of well completion techniques is being reviewed. The literature search includes the consideration of geology, geochemistry, reservoir characteristics, materials performance, and well failure modes. Well histories on how wells have been completed have been obtained for East Mesa, Baca, Roosevelt Hot Springs, and the Salton Sea. A set of intermediate variables, such as the frequency of workovers, is being developed. This list of variables will allow a mathematical representation of completions that will completely determine LCC. This list will also facilitate the converting of engineering data, e.g., the skin factors of slotted pipe, into LCC drivers.

The development of the LCC model has been initiated through a review of existing cost models and cost estimating literature. A simple, highly aggregated model has been developed as a guide to determining the completion cost categories that have the greatest effect on total well costs. These significant categories will be given increased attention during the detailed analysis phase. A preliminary work breakdown structure (WBS) has been generated for the initial completion costs and for the well operation

and maintenance costs. The refinement of the cost model and the WBS is continuing. A thermodynamic model of well performance at the wellhead has been initiated. The model will be included in the system benefit module.

The literature review did not reveal any existing models that adequately treat the operating and maintenance costs of a well or the capital costs of completions. No petroleum engineering text books on modeling field operation costs or on systems approaches to characterizing field operations costs were found. In some states, oil and gas commission records include workovers and well repairs and are potential sources for statistical data determining the life history of wells. However, California does not keep maintenance records for geothermal wells.

The Petroleum Information Corporation records in Bakersfield, CA, appear to include sufficient detail so that the basic ways in which wells are being completed and the capital costs of those completions can be analyzed. However, the effectiveness of these completions will be a function not only of the initial costs but also of the output of the completion and the cost to maintain the completion. Such data are apparently available only through field operators. Sandia's generic wells have been reviewed and furnish baseline data for the initial costs of completing a well.

Information has been obtained for generating cost relationships for logging services, nitrogen stimulation services, and workover rigs. Perforation costs are under study. Previously funded studies of descaling methods are under review for application to the LCC model. Several small modifications to these results have been incorporated for operating and maintenance cost projections of inhibitor equipment.

An engineering data requirements list has been made for the data needed to determine the initial costs of completions. The identification of the data required for workover costs, operating and maintenance, performance, failures, etc., is in progress. Pump cost relationships have been developed for inclusion in the intermediate variable model. These relationships consider capital costs including installation, spares, maintenance, and utility costs. The equations are also being refined for application within the detailed model.

The mathematical relationships between the intermediate variables and life cycle cost/benefit are being developed. The effects of discounting practices, service life, and prospect period are being reviewed for inclusion in the model. Examples of intermediate variables and how they effect LCCs have been presented to Sandia. The complete list of intermediate variables is in preparation and should be finished soon. This list, together with a more comprehensive example, will be developed and presented to Sandia for review next quarter.

The overall structure of the computer code is being planned, and the code requirements to model the relationship between intermediate variables and life cycle cost/benefit are being determined.

Example calculations have been performed to determine the significance of

1. Productivity,
2. Mean time between maintenance actions,
3. Cost of maintenance actions,
4. Delays, and
5. Other completion-independent costs.

The results of these examples are being analyzed for presentation to Sandia. Example calculations have proved useful as a way of identifying basic data categories and the kind of data needed. For example, the need for data on delay time was identified through example calculations.

7. LOST CIRCULATION CONTROL METHODS

A major contributor to the high costs experienced in geothermal well drilling is lost circulation. Drilling fluid loss causes several undesirable drilling conditions, including diminished cooling of the bit and removal of bottomhole chips. Also, most drilling fluids are expensive, and transportation of additional fluid additives to the drilling site results in costly time delays as well as in increased direct material/services costs. Lost circulation problems, in general, are not well-defined nor readily understood, and methods and materials used to control lost circulation problems are even more ill-defined. The approach to the development of lost circulation control methods is to (1) characterize and define in detail the operational and technical parameters of the problem, (2) formulate possible solutions, and (3) conduct the indicated research and development required for identifying effective control or prevention methods, materials, and/or equipment. Projects are currently proceeding with the objectives of (1) designing and fabricating a facility to test lost circulation materials and completion techniques at simulated geothermal well conditions and (2) evaluating the techniques and hardware that enable drilling through lost circulation zones in geothermal wells. The status and progress of these activities are described within this section.

An assessment of the state of the art of mapping lost circulation zones in geothermal wells has been completed. The assessment identified several methods by which to map lost circulation zones in geothermal wells at temperatures to 275°C (527°F) and higher in some cases. No single tool is capable of completely mapping lost circulation zones. Rather, multiple tools, usually two, are required in order to obtain sufficient information. No single method is the best in all cases. However, a new combined sound-temperature log has been used successfully in several diverse applications. This tool ranked highest of the 25 tools evaluated. The future availability of high-temperature geothermal logging tools having a 260° to 288°C (500° to 550°F) and a limited 316°C (600°F) capacity appears promising, with several companies currently updating existing technology or developing new technologies for use in high-temperature environments.

Projects to determine the geological characteristics of lost circulation zones and to collect, collate, and analyze industry experience concerning the causes, prevention, and remedy of lost circulation in geothermal environments were completed during fiscal year 1980. These projects added to baseline data and identified areas in which data are incomplete or nonexistent.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND:

———— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

7.1 Lost Circulation/Completion Test Facility

Sandia National Laboratories

Technical Consultants: V. Behr (505) 846-0301

J. Kelsey (505) 844-6968

E. Hoover (505) 844-7315

Project Objective

The first objective of this project is to construct a facility that will provide the capability to test lost circulation/completion materials and techniques at simulated geothermal conditions. Following the construction of the facility, the evaluation of materials and techniques used for problems in completion and lost circulation in geothermal wells will begin. The final objective is to recommend the proposed solutions that stand the best chance for success in the field; thus, the facility will serve as a final screening facility before field testing.

Project Status

The detailed design of the facility is approaching the final stages, and hardware procurement and fabrication are continuing. The plans for the construction modifications necessary for the building of the facility are ongoing. The computer necessary for system control and data acquisition has been received.

Quarterly Progress

During this reporting period, the detailed design of the facility and the procurement and fabrication of hardware were continued.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ————— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

7.2 Lost Circulation Material Screening Apparatus

Sandia National Laboratories

Technical Consultants: V. Behr (505) 846-0301
J. Kelsey (505) 844-6968

Project Objective

The objective of this project is to fabricate an economical screening apparatus that will be simple enough to permit the testing of a large matrix of materials in a short period of time. The apparatus will be used to evaluate the relative performance of a large number of lost circulation materials to determine which materials should be tested first in the Lost Circulation/Completion Test Facility (see Section 7.1). This preliminary evaluation procedure will allow work in the Lost Circulation/Completion Test Facility to be concentrated on the most promising materials, conserving both time and material in the operation of the facility.

Project Status

A suitable apparatus has been acquired, modified, and brought to an operational status for ambient temperatures. Preliminary testing has been initiated to validate test procedures and check out the apparatus.

Quarterly Progress

A standard API lost circulation tester, shown in Figure 7-1, was procured. In order to more closely simulate the geothermal environment, the tester was modified as depicted in Figure 7-2. A heater jacket has been added to the tester to increase the temperature capability to 149°C (300°F). The heater jacket will allow the evaluation of the effect of temperature on the performance of lost circulation materials. Also, since lost circulation in geothermal drilling frequently occurs in fracture-dominated formations, the standard API slots in the tester were replaced with 15.2-mm (6-in.) long slots having either parallel or tapered walls. Preliminary tests were started near the end of this reporting period to validate the operation of the apparatus.

Figure 7-1. Lost Circulation Test Cell

Figure 7-2. Geothermal Lost Circulation Test Apparatus

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND:

— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

7.3 Evaluation of Techniques and Hardware for Drilling Through Lost Circulation Zones

Contractor: Maurer Engineering, Inc.
Principal Investigator: D. Dareing (713) 683-8227
Contract Period: 1 September 1980 to 30 April 1981
Contract Number: 62-7201 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project is to evaluate the techniques and hardware that permit drilling through lost circulation zones in geothermal wells. Techniques and hardware including

1. Concentric drill pipe,
2. Low-density drilling fluids, and
3. Fluid aeration through a parasite string

will be evaluated on the basis of performance, risk, cost, and availability.

Project Status

The project was completed during this reporting period. The preparation of the final report is under way, and the report will be published separately during the next quarter.

Quarterly Progress

Geothermal drilling often takes place in high elevations, where ground water tables are considerable distances, i.e., about 305 meters (1,000 feet), below rig level. Above the water table, the formation pressure gradient is zero. Below the water table, the formation pressure increases with depth. The pressure unbalance between the wellbore drilling fluid and the formation pressures drives drilling fluid into the formation when natural fractures or caverns are encountered at the drill bit. When drilling fluid is pumped into the natural fractures or caverns, it does not return to the rig. Therefore, circulation of the drilling fluid is lost.

One way to combat lost circulation is to eliminate the unbalanced pressure between the drilling fluid and the formation. The objective of

this study was to evaluate balanced pressure drilling techniques for geothermal drilling. The following drilling techniques were evaluated:

- Aerated drilling mud
- Parasite tubing
- Concentric drill pipe
- Low-density fluids

The evaluation was based on the performance, risk, availability, and cost of each drilling technique. A summary of the evaluation results and the preliminary conclusions follows.

Evaluation Results — The aerated drilling technique ranked highest in the evaluation because of its performance capability and the level of experience with this method (Table 7-1). The parasite tubing method also ranked high. However, a composite system incorporating parasite tubing with low-density drilling fluids appears to have an even greater potential for combating lost circulation. The main disadvantage of this hybrid system is the high cost of low-density fluids. Further study of this hybrid system appears warranted because of its high performance potential.

It was not the intent of the evaluation to rule out any of the balanced-pressure techniques for geothermal drilling. Most of the techniques evaluated have been used successfully in combating lost circulation, and each has merit. The ability of each technique to perform against specific operational requirements was weighted heavily in the evaluation. Under other performance requirements, the evaluation results might be different.

According to the evaluation of balanced-pressure drilling techniques, aerated water, i.e., drilling fluid aerated at the surface, has the best overall balance of performance, risk, schedule, and costs. Even though the drilling fluid pressure cannot be made to exactly balance formation pressure, the unbalanced pressure can be reduced from a maximum of 6.9 MPa (1,000 psi) to about 0.35 MPa (50 psi). The 0.35-MPa (50-psi) condition is within acceptable Δp limits. The aerated-water pressure gradient very nearly matches the assumed formation pressure gradient when the air to water ratio is 19:1. This ratio is within the limits of nonfoam aerated fluids; however, heading is a potential problem. The greatest risk is corrosion to the drill string and other drilling equipment. Aerated water is presently being used in geothermal drilling, and it is not surprising that this technique received a high rank in the evaluation.

The parasite tube method using a low-density fluid as a drilling mud has the potential of outperforming the aerated drilling technique. A parasite tube would be attached to the 34.0-cm (13-3/8-in.) casing, and air would be injected at a rate to produce a 10:1 air/mud mixture within the 34.0-cm (13-3/8-in.) casing. This air/mud mixture would balance the drilling fluid and formation pressure at the point of air injection. A low-density fluid having a density of 735 kg/m³ (45.88 lb/ft³), which matches the density of 288°C (550°F) water, would balance the borehole pressure everywhere below the air injection point.

Table 7-1
Evaluation Summary

	Weight %	Concept*						
		A	B	C	D	E	F	G
<u>Performance</u>								
• Pressure Balance	15	14	14	10	10	2	5	15
• Pressure Maintenance	5	0	0	5	0	0	2	5
• Reliability	10	8	8	10	8	9	9	9
• Maintenance	<u>10</u>	9	3	9	6	9	8	8
Subtotal	40							
<u>Risk</u>								
• Stage of Equipment Development	15	15	15	14	10	10	15	15
• Drilling and Completion Experience	<u>15</u>	15	15	7	7	3	12	10
Subtotal	30							
<u>Schedule</u>								
• Equipment Availability	10	10	10	9	9	8	10	10
• Personnel Training	<u>10</u>	10	10	8	6	5	9	9
Subtotal	20							
<u>Cost</u>								
• Comparison with Aerated System	<u>10</u>	<u>8</u>	<u>5</u>	<u>10</u>	<u>4</u>	<u>8</u>	<u>0</u>	<u>0</u>
Total Score	100%	89	80	82	60	54	70	81

- * Concept Identification
 A--Aerated drill fluid (aerated mud)
 B--Aerated drill fluid (foam)
 C--Parasite tube method
 D--Concentric drill pipe
 E--Jet sub
 F--Low-density drilling fluid
 G--Low-density parasite tube

With reduced costs and increased experience, the parasite tube technique could be ranked higher than the aerated system. Because of its potential to completely eliminate the difference between formation and wellbore pressures, the parasite tube technique appears to warrant further development. The main problem with the technique is that the cost of low-density fluids must be substantially reduced.

Evaluation Conclusions -- Based on the evaluation, the following preliminary conclusions were drawn:

1. Aerated water with a 19:1 air/water ratio reduces the maximum pressure unbalance from 6.9 to 0.35 MPa (1,000 to 50 psi).
2. The parasite tube method, used with a 735-kg/m³ (6.13-lb/gal) low-density drilling fluid, can eliminate pressure unbalance. A parasite tube would have to be attached to the 34.0-cm (13-3/8-in.) casing because there is not enough annular space between 24.5-cm and 34.0-cm (9-5/8-in and 13-3/8-in.) casing to attach a workable tube.
3. The best way to aerate water at the bottom of 24.5-cm (9-3/8-in.) casing is with concentric pipe. An air/water ratio of 14:1 would produce a maximum pressure unbalance of 1.2 MPa (180 psi). The pressure unbalance would be into the formation over part of the drilling interval and into the borehole over part of the drilling interval.
4. The jet sub method has no pressure control advantage over the straight, aerated mud method.
5. Low-density mud alone has no pressure control advantage. This technique must be used with the parasite tube or concentric pipe techniques in order to be effective.
6. Air drilling is often restricted to the top 305-meter (1,000-foot) section, where there is no water, or in the superheat reservoir in The Geysers.
7. Conventional mud drilling with 1,198-kg/m³ (10-lb/gal) mud produces an unbalance pressure condition from spud-in. The pressure unbalance reaches a maximum of 10.3 MPa (1,500 psi) at 1,829 meters (6,000 feet).
8. The main problem in balancing wellbore pressure with formation pressure is in matching the 775-kg/m³ (48.4-lb/ft³) heated water density caused by 288°C (550°F) temperatures.
9. All of the pressure balance techniques considered are fully developed, fielded and have been used successfully in combating lost circulation in oil and gas drilling.

8. SUPPORTING TECHNOLOGY

The proper design of improved and new drilling and completion equipment and materials requires a firm understanding of the special requirements and criteria necessary to operate in the geothermal environment. The objective of supporting technology is to acquire and provide the information necessary to develop improved and new designs, techniques, and/or materials. The approach to providing the required analytical and experimental data includes the development of appropriate computer codes, construction or modification of test facilities, and research into the performance of materials. Currently, projects are under way (1) to expand capabilities to predict transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells, (2) to determine the optimal number, size, and placement of nozzles used for bit cooling and cleaning, (3) to optimize the design of polycrystalline diamond compact (PDC) geothermal bits by studying the stress buildup and chip formation processes of rock cutting tools utilizing PDC cutters, (4) to study the metallurgical composition of conventional drill stem and make compositional changes in the drill stem material to maximize its chemical resistance to geothermal H_2S environments without large sacrifices in its mechanical properties or cost, and (5) to extend laboratory capabilities for high-speed/high-torque bit testing. The status and progress of these activities are described within this section.

A computer model for calculating the stress induced in drag-type cutters and for modeling the tool/rock interaction has been developed and applied to the use of steel cutters in sandstone. The model is a finite element code called TOODY, which has been used extensively in predicting shock wave propagation. The use of the code is continuing for calculating stresses in the PDC cutter/rock interaction studies.

A computer model for predicting the temperatures of borehole fluids and downhole equipment under real-time, flowing conditions has been formulated, documented, and verified. The model analyzes single-phase flow during drilling, production, or injection. The undisturbed geothermal temperature gradient must be specified. The validation of the model involved the comparison of computer predictions with actual field measurements of temperature in oil and gas and geothermal wells. The model is being modified to predict transient wellbore temperatures for compressible fluids in the single-phase flow regime, as well as simulation of two-phase flow.

The development of an operations-based model for analyzing the effects of improved technology on well costs has been completed. The model has been used to predict the percentage reduction in well cost obtainable with improved penetration rates. Other technological improvements are currently being evaluated by the use of the model.

A laboratory facility for use in optimizing drill bit hydraulics has been designed and fabricated at Sandia. Drilling Research Laboratory, Salt Lake City, Utah, has been modified to provide torque capabilities to 13,600 N·m (10,000 ft·lb) and rotary speeds to 500 rpm.

The experiments on coated elastomeric seals were completed. Two coating techniques were used. A 0.037-mm (0.0015-in.) thick film of Parylene C was deposited onto elastomers by Union Carbide's vapor phase, pyrolytic method, while a 0.038-mm (0.0015-in.) thick film of tetrafluoroethylene (TFE) was deposited on other samples by glow discharge polymerization, a diffusion-bonding technique. Both coatings provided significant environmental resistance to brine, temperature, and pressure; however, the Parylene C-coated equipment lost flexibility and adhesion when used in dynamic seal applications. Delamination was observed when Parylene C-coated seals were evaluated as a drill bit seal at 200°C (392°F) and 90 rpm in the presence of grease and an abrasive. TFE proved to be the more successful coating in dynamic applications. Dynamic wear tests showed that TFE-coated O-rings did not delaminate, ran cooler than noncoated rings, and exhibited improved abrasion resistance.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND:

————— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

8.1 Bit Hydraulics Studies

Sandia National Laboratories
Technical Consultant: D. Glowka (505) 844-3601

Project Objective

The objective of this project is to optimize the design of bit hydraulics for geothermal drill bits. Analytical and experimental investigations are being conducted to determine the optimal position, size, and placement of nozzles used for cooling and cleaning purposes. A bit hydraulics laboratory has been built in order to visualize the flow field along the bit face and provide measurements of bottomhole pressure gradients, cutter heat transfer coefficients, and chip removal capability.

Project Status

A program plan and technical investigation procedure have been formulated. A flow channel has been built and used to verify a new technique for measuring heat transfer coefficients on PDC cutters. This technique is one of several types used to assess the hydraulic performance of drill bits. These measurements are being made in a test stand which allows bit rotation in a transparent simulated borehole while fluid is pumped through the bit. Reliable operation of this facility has been achieved, and routine testing is underway.

Quarterly Progress

During this reporting period, progress was made in verifying the techniques for measuring cutter convective heat transfer coefficients and in achieving the reliable operation of the bit hydraulics test stand.

Cutter Heat Transfer -- As previously reported, a flow channel was built to provide a uniform flow field past a cutter instrumented with convective heat transfer gages. These gages, similar in size and shape to strain gages, are thin-film, temperature-dependent resistors. Hot-wire anemometry circuits are used to maintain the resistance and, therefore, the temperature of the gages at fixed values. Thus, measurements of the current and voltage drops across the gages are sufficient to permit the calculating of the convective heat transfer coefficients on the surfaces to which the gages are mounted.

The results of the verification testing of this measurement technique are shown in Figures 8-1 and 8-2. These results were obtained by mounting a gage on a 15.9-mm (0.625-in.) diameter cylinder placed in cross-flow. Measurements were taken for various water-flow velocities, V , and angles, θ , between the flow stagnation point and the gage location on the cylinder.

Figure 8-1. Local Convective Heat Transfer Coefficient Measurements for a Cylinder in Crossflow

Figure 8-2. Mean Convective Heat Transfer Coefficient for a Cylinder in Crossflow

These measurements were then converted into values of heat transfer coefficient, h , and Nusselt number, $Nu = \frac{hd}{k}$, where d = diameter of the cylinder and k = thermal conductivity of the test fluid.

The behavior of the data in Figure 8-1 is as expected. The heat transfer coefficient increases with the Reynolds number, Re_D , at a given angle, θ . Also, for a given Re_D , the heat transfer coefficient first increases with angle, falls sharply near $\theta = 90^\circ$, where flow separation occurs, and then increases moderately to a nominal value at the back of the cylinder. Thus, the data reveal that the measurement technique has adequate sensitivity for its intended use in the bit hydraulics test stand, i.e., to measure heat transfer coefficients on PDC bit cutters in simulated downhole flow fields.

The accuracy of the measurement technique was ascertained by integrating the curves of Figure 8-1 to determine the mean convective heat transfer coefficient over the surface of the cylinder. These data points are presented in Figure 8-2, along with the heat transfer correlation obtained from the literature and verified by other investigations using different measurement techniques. The current measurement technique, which is more ideally suited to the measurement of local heat transfer coefficients, is seen to provide data that agree closely with those of other investigators.

With the accuracy of the technique verified, baseline data for a PDC stud placed in a uniform flow field were obtained. These data are presented in Figure 8-3 for four different locations on the stud. It is interesting to note that location No. 4 experiences the lowest values of h of all locations tested. This characteristic is important in the thermal analysis of the stud during cutting because No. 4 is the location that receives the largest amount of heat input due to friction.

Work with convective heat transfer coefficients will continue during the next reporting period with measurements of PDC bit cooling capabilities being taken in the bit hydraulics test stand.

Test Stand Operation -- After the installation of a new drill pipe in the bit hydraulics test stand, the repeatable rotation of the bit during flowing was achieved for the first time in January 1981. Since that time, testing on a routine basis has confirmed the reliable operation of the bit rotation, main fluid flow, and dye injection systems.

The first series of tests run in the facility were dye injection tests for a 16.5-cm (6.5-in.) bit blank. This bit blank has a flat face without cutters but with the same nozzle configuration as the Sandia 16.5-cm (6.5-in.) PDC bit that will be run during the next reporting period. There were two purposes for testing the bit blank. First, it was necessary to verify the operation of the facility, and a simple hydraulic configuration appeared to be the best choice for this purpose. Second, information on the baseline flow patterns without studs was desired for comparison with numerical flow models now being developed.

Typical results for the bit blank test series are shown in Figures 8-4 and 8-5. In each of these figures, dye is flowing from a single nozzle,

Figure 8-3. Local Convective Heat Transfer Coefficient Measurements for a PDC Stud in Crossflow

Figure 8-4. Typical Flow Pattern in Bit Blank Test

Figure 8-5. Typical Flow Pattern in Bit Blank Test

while clear water is flowing from the remaining nozzles. Blue food coloring at a concentration of 0.3% was chosen as the test dye due to its biodegradable and nontoxic characteristics.

The test series consisted of sequentially moving the dye tube from nozzle to nozzle and photographing the resulting flow patterns for a test matrix of three bit rotational speeds and three flow rates. An analysis of the results is currently under way.

The Sandia 16.5-cm (6.5-in.) PDC stud bit shown in Figure 8-6 is being prepared for testing. The bit has been instrumented with 28 convective heat transfer gages. The preparation for testing consists of connecting the leads for these gages to leads that run from the test stand slip rings, through which measurements can be made.

The testing of this bit is expected to begin next quarter and continue for at least 3 months. This testing will consist of photographing flow patterns and measuring convective heat transfer coefficients and bottomhole pressure gradients for a variety of hydraulic configurations, bit rotational speeds, and fluid flow rates.

Figure 8-6. Sandia 16.5-cm (6.5-in.) PDC Stud Bit

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

8.2 Drill Stem Corrosion

Sandia National Laboratories

Technical Consultant: R. Salzbrenner (505) 844-5041

Project Objective

The project objective is to study the metallurgical composition of drill stem presently available and to make compositional changes in drill stem material to maximize its chemical resistance to the geothermal H₂S environment without large sacrifices to its mechanical properties or cost.

Project Status

An Internal R&D research report was issued. The test facility design and fabrication were completed. Compositional changes to the drill stem material were defined, and conventional drill stem material suitable for the corrosion fatigue study was identified. The dual-phase steel alloys have been made and the conventional drill stem material delivered. The processing of the dual-phase alloys and the fabrication of the specimens for the heat treatment experiments have been completed. Fatigue tests have been completed in a variety of environments, using Grade E drill stem material to establish the baseline data. During this quarter, tests have been carried out to examine the effect of heat treatment and rolling direction orientation on the tensile strength of dual-phase steel.

Quarterly Progress

The previous quarterly report described tensile test results for the dual-phase steel in the step quenched heat treatment, in both the transverse and longitudinal orientations. Figure 8-7 shows the test results for the transverse orientation of the dual-phase steel, Fe plus, by weight percent, 1.7Si-0.1V-0.1C, that has been heat treated by the intermediate quenching procedure. The behavior of each of the parameters measured, i.e., yield strength, ultimate strength, total elongation, and reduction in area, shows very little change with annealing temperature. This behavior is expected because of the "self-balancing" nature of the microstructure during heat treatment. At low annealing temperatures, the alloy has a low volume fraction of martensite, but this martensite is high in carbon, which results in the martensite having a high strength per unit volume. At high annealing temperatures, the alloy gains a higher volume fraction of martensite, but the carbon level in the martensite is low, and, thus, the strength of the martensite is low. Dual-phase steel alloys behave much like composite materials in that the strength of the material is largely controlled by one phase, the martensite. Thus, at low annealing temperatures, the strength is provided by a small amount of very high strength martensite, while, at the high annealing temperatures, the strength is provided by a large amount of lower strength martensite. A balance is thus obtained so that the strength remains approximately the same, independent of annealing temperature.

Figure 8-7. Tensile Test Data for Intermediate Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.75Si-0.1V-0.1C with Longitudinal Orientation. Tested at 25°C (77°F) with $\epsilon = 10^{-3}/s$.

Figure 8-8 shows the tensile test results for the transverse orientation with step quench heat treatment. A comparison of Figures 8-7 and 8-8 shows the step quenched material to have a significantly higher strength at the higher annealing temperatures than does the intermediate quenched material. The intermediate quenched material does, however, exhibit a greater ductility as measured by total elongation and reduction in area. The strength/ductility combinations can be chosen to meet requirements for specific applications. Other properties, such as corrosion fatigue resistance, must also be considered in order to determine the appropriate heat treatment for a particular use.

Corrosion fatigue measurements on one heat treatment of the dual-phase steel have been made. The heat treatment was the step quench that produces a ferrite/martensite microstructure in which the martensite is encapsulated by the ferrite. The crack growth rate of the dual-phase steel in a dry air environment is shown in Figure 8-9. This growth rate is below that measured in the Grade E material. The crack growth rate increases in the dual-phase steel when the testing environment is the NACE brine solution. Test results are shown in Figure 8-10 for the NACE brine. Although there is an increase in crack growth rate for the dual-phase alloy when the environment is changed from dry air to brine, the rate is still below that for the Grade E material in those environments.

When hydrogen sulfide is added to the testing environment, the crack growth rates for the dual-phase steel increase significantly, as shown in Figure 8-11. The schematic representation of the crack growth rates for the dual-phase steel as a function of environment is shown in Figure 8-12. Comparatively, the H_2S causes a greater increase in the crack growth rate in the step quenched dual-phase material than in the Grade E material that was quenched and tempered. Figure 8-13 shows a direct comparison of the Grade E material and the step quenched dual-phase material in the H_2S -saturated brine. The dual-phase alloy appears to have a lower crack growth rate at lower stress intensity levels, while the Grade E alloy has a lower crack growth rate at higher stress intensity levels. The crossover point is in the 207 to 228 MPa (30 to 33 ksi) range.

Further experimentation will be done to extend these curves into the low 10^{-7} crack growth ranges. Also, different heat treatments of the dual-phase steel will be carried out to determine what effect heat treatment has on crack growth rates. These tests will be performed as the samples and machine time become available.

Figure 8-8. Tensile Test Data for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C with Longitudinal Orientation. Tested at 25°C (77°F) with $\epsilon = 10^{-3}$ /s.

Figure 8-9. Fatigue Test for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in Dry Air ($\Delta k = K_{\text{max.}} - K_{\text{min.}}$, $0.1 K_{\text{max.}} = K_{\text{min.}}$)

Figure 8-10. Fatigue Test for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in NACE Brine ($\Delta k = K_{\text{max.}} - K_{\text{min.}}$, $0.1 K_{\text{max.}} = K_{\text{min.}}$)

Figure 8-11. Fatigue Test for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in H₂S-Saturated NACE Brine ($\Delta k = K_{\max.} - K_{\min.}$, $0.1 K_{\max.} = K_{\min.}$)

Figure 8-12. Fatigue Test Results for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C in Various Environments ($\Delta k = K_{\text{max.}} - K_{\text{min.}}$, $0.1 K_{\text{max.}} = K_{\text{min.}}$)

Figure 8-13. Fatigue Test Results for Step Quenched, Dual-Phase Alloy Fe Plus, by Weight Percent, 1.7Si-0.1V-0.1C and Grade E Materials in H₂S-Saturated Brine ($\Delta k = K_{\text{max.}} - K_{\text{min.}}$, $0.1 K_{\text{max.}} = K_{\text{min.}}$)

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE	
<u>ROCK MECHANICS</u>														
CALCULATIONS														
TOOL														
STRESSES														
FRICTIONAL FORCES	COMPLETED													
HEAT INPUT	COMPLETED													
WEAR	COMPLETED													
THERMAL ANALYSIS														
FLUID STUDIES														
EXPERIMENTS														
CHIP FORMATION	COMPLETED													
FORCE DETERMINATION														
TEMPERATURE														
MEASUREMENTS														
FRICTION MEASUREMENTS														

LEGEND: ——— ACTIVITY PERIOD
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○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

8.3 Rock Mechanics for Polycrystalline Diamond Compact Cutters

Sandia National Laboratories
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The project objective is to conduct research on and testing of the chip formation process of rock cutting tools utilizing polycrystalline diamond compact (PDC) cutters in order to optimize the design of bits using these cutters.

Project Status

A study of the procedures necessary for conducting chip formation testing was initiated. The modeling of the rock/tool interface has begun. Calculations of tool stresses and frictional forces were completed. Calculations of heat input were completed, and wear calculations are continuing. A thermal analysis is being conducted.

Quarterly Progress

Research and development continued for the purpose of reducing the cost of drilling geothermal and oil wells. As part of this effort, drag bits are being designed using PDC cutters. Finite element models of the drag bit cutting process are being developed with the ultimate objective of optimizing drill bit design. During this quarter, progress was made in testing to verify the material model.

Basic material tests to characterize the Berea sandstone sample were completed by Atkinson, Noland, and Associates of Boulder, Colorado. A final report has been received. The testing of more complicated specimens under conditions that approximate those encountered during in situ drilling is in progress at Sandia. These tests are approximately one-half finished. Also, single-cutter tests have been started at Sandia. High-speed movies and force measurements are being made during these tests. Preliminary analyses of the prototypic and single-cutter tests have been completed.

Work in the next quarter will be directed towards completing the prototypic and single-cutter tests, making improvements in the constitutive model for rock, and reanalyzing the tests using data obtained in the basic material tests.

FISCAL YEAR 81

LEGEND: **ACTIVITY PERIOD** **PLANNED START** **PLANNED COMPLETION**
 RESCHEDULED **STARTED** **COMPLETED**

8.4 Modification and Extension of Testing Capabilities

Contractor: Drilling Research Laboratory, Inc. (DRL)
Principal Investigator: A. D. Black (801) 582-2220
Contract Period: 12 September 1979 to 31 May 1981
Contract Number: 13-8785 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to modify and extend testing capabilities in the following areas:

1. Selection and acquisition of pertinent rock samples and specifications,
2. Torque and rpm capability for testing high-speed/high-torque bits,
3. Bit dynamic data acquisition, and
4. High-pressure/jet-drilling testing capability.

Project Status

Rock specification data were compiled, and potential sources of rock specimens were identified. The design and assembly of the high-speed/high-torque facility were completed. A high-rate data acquisition computer program was completed. The testing on a pulsation dampener supplied by Hydrodyne Industries, Inc., was completed. Conceptual ideas for the high-pressure facility were evaluated, and the design and fabrication of the facility are continuing.

Quarterly Progress

High-Torque Capabilities -- A temporary controller for the two 125-hp drive motors was fabricated. With the temporary controller installed, tests were performed that demonstrated the utility of the new system. The system is now operational and was used during a full week of Stratapax™ bit testing for Sandia. The permanent control panel will be completed upon receipt of a few long-delivery-time items.

High-Speed Hydraulic Drive System -- The 500 to 1,000 rpm high-speed drive system has been designed. During January 1981, a set of full-scale layout drawings was completed to insure proper space requirements and equipment attachments. Working drawings have been initiated, and some raw materials have been ordered. The bulk of the remaining materials was ordered in February 1981.

The 300-hp hydraulic supply is scheduled for delivery by the second week in April 1981. It is anticipated that the fabrication of the high-speed drive will be completed by the same time frame.

High-Pressure Capabilities -- The high-pressure pulsation dampener concepts from both Hydrodyne, Inc., and Hydril have been examined. Drawings from Hydrodyne are still pending. Upon receipt of these drawings, a high-pressure chamber will be fabricated according to Hydrodyne's design.

In addition to the Hydrodyne unit, arrangements are being made to purchase a 41.4-MPa or 68.9-MPa (6,000-psi or 10,000-psi) experimental pulsation dampener from Hydril. Data with differing pressure media in the dampeners will be obtained and exchanged.

The design of a high-pressure reduction system from HITCO, based on the results of testing on a purchased, low-pressure, experimental unit, is being pursued. Drilling mud will be pumped through the unit, and pressure data will be collected and sent to HITCO so that the data can complete a system design using several HITCO pressure drop units. Another system utilizing fixed and variable chokes is also being completed in case the HITCO test does not prove satisfactory.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

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8.5 Development of an Advanced Wellbore Thermal Code

Contractor: Enertech Engineering and Research Co.
Principal Investigator: G. R. Wooley (713) 521-9294
Contract Period: 25 January 1980 to 31 December 1981
Contract Number: 46-5670 and 74-2300 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project is to develop an advanced computer code for predicting transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells. The development of the code will encompass

1. The modification of the existing, single-phase fluid code to allow
 - a. A variable-tubing flow area,
 - b. Separated, multiple fluids in the wellbore, and
 - c. The provision for a deviated wellbore; and
2. Advanced code development providing for
 - a. The formulation of single-component, compressible flow in a wellbore,
 - b. The formulation of multicomponent, compressible flow in a wellbore, and
 - c. The reconstruction of the existing code to include compressible, multicomponent flow.

A series of technical articles illustrating the practical use of the computer code will also be prepared and published under this project.

Project Status

The project was initiated in January 1980. The effort to modify the existing GEOTEMP code to handle deviated holes, variable tubing areas, and multiple fluids was completed and checked out. The Part I report, covering the modified single-phase wellbore model and the compressible single-phase wellbore model, was completed and submitted to Sandia. The compressible single-phase wellbore model was thoroughly tested, and several minor errors were corrected. Work on the cuttings transport model is continuing. The preparation of the first technical article on the use of GEOTEMP code was initiated in January 1981.

Quarterly Progress

Cuttings Transport Model -- A working computer test program of the solids transport model discussed in earlier progress reports has been evaluated. Some minor deficiencies in the earlier formulation have been corrected.

The results of two early test cases were based on the following typical drilling situation:

Penetration rate: 0.0051 m/s (60 ft/h)
Hole diameter: 0.20 meter (7-7/8 inches)
Drill pipe diameter: 0.11 meter (4-1/2 inches)
Gas flow rate: 1.89 m³/s (2,000 scfm)
Average cutting diameter: 0.01 meter (1/2 inch)
Hole depth: 1,000 meters (3,000 feet)
Initial pressures: 1,101 kPa (147 psi)
551 kPa (73.5 psi)

The initial conditions were determined in the following way. The initial pressure was used to compute the initial gas density. The gas density and gas flow rate were used to determine the mass flow rate of the gas. The mass flow rate of the solids was determined from the penetration rate, bit size, and solids density. The relative velocity of the solids with respect to the gas was determined, assuming the particle weight was balanced by the fluid drag of the gas. From these quantities, the remaining variables can be determined through the basic flow equations.

The results of the 1,101-kPa (147-psi) bottomhole pressure test are given in Figures 8-14 through 8-17. Element lengths of 100 meters (328 feet) were found to give acceptable results. The pressure drop is very nearly linear, suggesting that the linearized equations should give acceptable results. Figure 8-15 shows the gas and solids velocities along the well. Again, the velocities appear very nearly linear. Figure 8-16 shows the gas densities in the wellbore. Because of the direct tie to the pressures, again, very linear performance is seen. Figure 8-17 shows the solids volume fraction. These results look somewhat erratic initially, which may reflect problems with the initial conditions or with the numerical method.

The lower pressure condition, 551 kPa (73.5 psi), is presented in Figures 8-18 through 8-21. The pressure (Figure 8-18), gas density (Figure 8-19), and volume fraction (Figure 8-20) are still reasonably linear, but the velocities (Figure 8-21) are beginning to look nonlinear enough to indicate deficiencies in the model. Note that the pressures shown in Figure 8-18 indicate that this is a fairly marginal case, with the exit pressure nearly atmospheric. A real drilling undertaking would probably be run at higher pressures, and the exit flow would be choked to maintain the required flow rates.

The cuttings transport model was revised to correct the aforementioned deficiencies. Some of the features and characteristics of the final model are presented in the following discussion.

1. In the first model, a momentum equation for each component was used. In the revised model, a single momentum equation is used for the mixture with a second momentum equation for the solids. The advantage of this treatment over the previous formulation lies in the evaluating of the frictional pressure drop. The friction factor for the mixture can be estimated using the Reynolds number

Figure 8-14. Pressure Results from the Solids Transport Model Test Using a Bottomhole Pressure of 1,101 kPa (147 psi)

Figure 8-15. Velocity Results from the Solids Transport Model Test
Using a Bottomhole Pressure of 1,101 kPa (147 psi)

Figure 8-16. Density Results from the Solids Transport Model Test
Using a Bottomhole Pressure of 1,101 kPa (147 psi)

Figure 8-17. Volume Fraction Results from the Solids Transport Model Test Using a Bottomhole Pressure of 1,101 kPa (147 psi)

Figure 8-18. Pressure Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (79.5 psi)

Figure 8-19. Density Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (73.5 psi)

Figure 8-20. Volume Fraction Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (73.5 psi)

Figure 8-21. Velocity Results from the Solids Transport Model Test Using a Bottomhole Pressure of 551 kPa (73.5 psi)

for the mixture, neglecting the contribution of the solid phase to the viscosity of the mixture but including all other effects. For the solids momentum equation, frictional pressure drop is currently neglected because of the difficulty in estimating the effective viscosity of the solids phase of the mixture. Rough calculations based on kinetic gas theory suggest that the frictional pressure drop for the solids phase is negligible.

2. Minor errors in evaluating the in-mixture densities have been correlated in the final model.
3. In the compressible flow model, inlet pressure and velocity were determined by the calculations being run "backward" from the exit pressure and velocity. It has been determined that the cuttings model will not run "backward". An explanation of this characteristic would require a theoretical study not appropriate to this project. However, a qualitative explanation has been proposed as follows. The momentum equation for the solids represents a diffusion equation, generalized by the addition of acceleration terms and written in an unconventional form. The diffusion equation is well-known for forming an ill-posed problem when the "backwards" boundary values are specified. The results of the numerical model "run backwards" are suggestive of the extreme sensitivity to initial conditions that is characteristic of the ill-posed diffusion problem.
4. The single-phase compressible flow model is now used to predict the inlet pressure and velocity for the solids transport model. The input to the single-phase model is determined based on density-weighted average properties similar to conventional two-phase flow pressure drop calculations. The cuttings model is run forwards and the exit pressure calculated. If the exit pressure falls below atmospheric, the estimated inlet pressure is increased, and the calculation is rerun to test the new inlet pressure. The single-phase model consistently underpredicts the inlet temperature and becomes less accurate as the gas flow rate approaches its lower limit. Sample cases typical of gas drilling operations have shown the single-phase calculation to err by greater than 25%.
5. Minimum gas flow rates exist below which cuttings cannot be carried out of the wellbore. The model response to inadequate gas flow is to generate a negative solids velocity somewhere in the wellbore. Beyond this point, the flow calculations do not make physical sense because a positive flow rate is required by the steady-flow assumption and the initial conditions. The code has been constructed so that the mass flow rate of the gas will automatically be increased enough to maintain solids flow. A warning message will be printed when inadequate flow rates are determined.
6. The sensitivity of the cuttings transport model to element size is shown in Figures 8-22 and 8-23. Figure 8-22 shows the sensitivity of the gas exit pressure to element length using typical air drilling parameters for a 2,438-meter (8,000-foot) well. For elements less than about 75 meters (246 feet) long, the exit pressure

Figure 8-22. Exit Gas Pressure Sensitivity to Element Length

Figure 8-23. Solids Volume Fraction Sensitivity to Element Length

is insensitive to element length. The GEOTEMP wellbore element is about 61 meters (200 feet) long, which falls in this range. Figure 8-23 shows the sensitivity of volume fraction to element length, as a measure of the accuracy of the solution of the solids momentum equation. Again, GEOTEMP elements are in the range of accuracy. To put everything into perspective, the difference in exit pressure for 250-meter (820-foot) elements and 50-meter (164 foot) elements corresponds to 2.5 kPa (0.4 psi), a trivial difference. The variation in volume fraction is about 2%.

7. A further test of the cuttings model was run for comparison with published air drilling models. A typical model was published by R. Angel¹ in 1958. For the following parameters,

Well depth: 2,438 meters (8,000 feet),
Penetration rate: 18.3 m/h (60 ft/h),
Bit diameter: 44.5-cm (17-1/2 in.), and
Drill pipe: 16.8-cm (6-5/8-in.) diameter,

Angel predicts an air volume flow rate of 2.67 m³/s (56,660 scfm). For cuttings 0.01 m (0.4 in.) in diameter, the cuttings transport model required 3.66 m³/s (7,750 scfm). Figures 8-24 through 8-27 give the results of these calculations. There are several reasons for this discrepancy. First, Angel used a single-phase flow model, which errs by greater than 25% near the minimum gas flow rate. Second, the 0.01-m (0.4-in.) particle size represents an upper bound. The air drilling literature^{2,3} maintains that particle size at the bit is about 0.01 meter (0.4 in.), and particle size decreases up the hole due to collisions and regrinding. Particle size at the exit is claimed to be powder size. The above flow calculations were redone (see Figures 8-28 through 8-31) with a 0.001-m (0.04-in.) particle size, i.e., a coarse sand. The minimum gas flow rate for this case was 2.36 m³/s (5,000 scfm). For realistic solid particle sizes, the solids transport predictions are comparable with conventional gas volume flow rate estimates.

Mist Drilling Model -- The development of the mist drilling model is well under way. The correlations of pressure, density, and enthalpy as functions of temperature have been programmed. Figures 8-32 through 8-35 show the performance of the correlations as compared to tabulated values.

The theoretical development of the mist flow-phase change model was completed this quarter. To simplify discussing the various two-phase flow models, three sets of definitions and equations have been compiled. Figure 8-36 summarizes the general relations for a one-dimensional multiphase flow model, Figure 8-37 simplifies the equations of Figure 8-36 for the cuttings transport model, and Figures 8-37 and 8-38 give the relations for a two-phase model with phase change. Reference to Figure 8-36 will make clear the simplifications used to develop the cuttings model and the phase-change model. A brief summary of the mist flow-phase change model follows:

1. Steady flow assumed for mass and momentum conservation.
2. Only two phases modeled.

Figure 8-24. Solids Transport Velocities Based on the Solids Transport Model by R. Angel¹

Figure 8-25. Gas Pressure Results Based on the Solids Transport Model by R. Angel¹

Figure 8-26. Gas Densities Based on the Solids Transport Model by R. Angel¹

Figure 8-27. Volume Fraction Results Based on the Solids Transport Model by R. Angel¹

Figure 8-28. Solids Transport Velocities Recalculated Using a More Realistic Particle Size

Figure 8-29. Gas Densities Recalculated Using a More Realistic Particle Size

Figure 8-30. Volume Fraction Results Recalculated Using a More Realistic Particle Size

Figure 8-31. Gas Pressures Recalculated Using a More Realistic Particle Size

Figure 8-32. Saturation Liquid Density Correlations of the Drilling Mist Model Compared to Tabulated Values

Figure 8-33. Saturation Vapor Density Correlations of the Drilling Mist Model Compared to Tabulated Values

Figure 8-34. Saturation Vapor Pressure Correlations of the Drilling Mist Model Compared to Tabulated Values

Figure 8-35. Liquid and Vapor Enthalpy Correlations of the Drilling Mist Model Compared to Tabulated Values

3. Single temperature assumed, which implies
 - a. No heat transfer between phases,
 - b. Thermodynamic equilibrium between phases, and
 - c. Single energy equation for mixture.
4. Only one volume fraction used explicitly (see Definition 5 of Figure 8-36).
5. No phase change in the cuttings model.
6. Temperature and velocities used as independent variables.
7. Integrated forms of balance equations used.

Two principal changes from the cuttings transport model were necessary for the phase-change model. First, the phase rule requires that the gas phase pressure can only be a function of a single variable. The most common and natural choice for independent variable is the temperature. Saturation pressure is typically correlated as a function of temperature, and a suitable correlation for water vapor was found in Reference 4. Similarly, liquid and vapor densities and enthalpies can be correlated as a function of temperature as well.

The second change is that the mass flow rate for each component is no longer constant. Further, the density is strictly a function of temperature, where previously it was strictly a function of velocity. Because of this relationship, it is possible to evaluate the mass supply term $\hat{c}$ in terms of the independent variables through the mass conservation equations. The full formulation and preliminary computer studies have been initiated.

The preliminary testing of the two-phase flow model with phase change was completed with good results. The numerical model appears to be stable, and the calculated results are qualitatively sensible.

Figure 8-39 shows the phase change explicitly. As the water droplets in the flowing stream vaporize, the mass flux of the water phase decreases, and, correspondingly, the mass flux of the steam phase increases.

Figure 8-40 shows the temperature of the flowing stream. The temperature falls in proportion with the phase change as the flowing stream is cooled by the vaporization of the water droplets. Simultaneously, the pressure, shown in Figure 8-41, drops so that the flowing stream is still at thermodynamic equilibrium.

Figure 8-42 shows the flowing stream velocities. The velocity of the liquid phase is very nearly the same as the gas phase, which suggests that a simplified mist drilling model could be modified to work a mixture problem as a pseudohomogeneous fluid problem.

The development of a two-phase steam production model based on conventional technology is being initiated.

Series of Technical Articles -- Work on this task was initiated in January 1981. Industry contracts have been made to discuss example cases

I. DEFINITIONS

1. ρ_a = LOCAL DENSITY OF COMPONENT a
2. $\bar{\rho}_a$ = IN-MIXTURE DENSITY OF COMPONENT a
3. ϕ_a = VOLUME FRACTION OF COMPONENT a
4. $\bar{\rho}_a = \rho_a \phi_a$
5. $\sum_a \phi_a = 1$
6. v_a = VELOCITY OF COMPONENT a
7. $G_a = \bar{\rho}_a v_a$ = MASS FLUX DENSITY OF COMPONENT a
8. $\rho = \sum_a \bar{\rho}_a$ = DENSITY OF MIXTURE
9. $\rho \dot{x} = \sum_a G_a$ = MASS FLUX DENSITY OF MIXTURE
10. $\dot{x}$ = DENSITY WEIGHTED VELOCITY OF MIXTURE
11. $u_a = v_a - \dot{x}$ = DIFFUSION VELOCITY OF COMPONENT a
12. $\hat{c}_a$ = MASS SUPPLY TO COMPONENT a
13. p_a = PARTIAL PRESSURE OF COMPONENT a
14. F_a = FRICTIONAL PRESSURE DROP OF COMPONENT a
15. g = GRAVITY FORCE
16. $\hat{p}_a$ = DIFFUSION FORCE OF MIXTURE ON COMPONENT a
17. ϵ_a = INTERNAL ENERGY OF COMPONENT a
18. $\hat{\epsilon}_a$ = ENERGY SUPPLY TO COMPONENT a

Figure 8-36. Summary of Mixture Relations for a One-Dimensional, Multiphase Flow Model

II. BALANCE EQUATIONS

CONSERVATION OF MASS

$$19. \quad \frac{\partial}{\partial t} \rho_a + \frac{\partial}{\partial z} G_a = \hat{c}_a \quad (\text{FOR COMPONENT } a)$$

$$20. \quad \sum_a \hat{c}_a = 0 \quad (\text{FOR MIXTURE})$$

CONSERVATION OF MOMENTUM

$$21. \quad \rho_a \frac{\partial}{\partial t} v_a + G_a \frac{\partial}{\partial z} v_a = - \frac{\partial}{\partial z} P_a + F_a + \bar{\rho}_a g + \hat{p}_a$$

$$22. \quad \sum_a (\hat{p}_a + \hat{c}_a u_a) = 0$$

CONSERVATION OF ENERGY

$$23. \quad \rho_a \frac{\partial}{\partial t} \epsilon_a + G_a \frac{\partial}{\partial z} \epsilon_a = - P_a \frac{\partial}{\partial z} v_a + F_a v_a + \hat{\epsilon}_a + Q_a$$

$$24. \quad \sum_a [\hat{\epsilon}_a + p_a u_a + \hat{c}_a (\epsilon_a + u_a^2/2)] = 0$$

III. CONSTITUTIVE EQUATIONS

$$25. \quad P_a = z_a (\rho_a, T_a) \rho_a T_a$$

$$26. \quad F_a = \frac{1}{2} \frac{f'}{D} \bar{\rho}_a v_a^2$$

$$27. \quad \hat{p}_a = \frac{1}{2} \sum_b c_d \rho_b (v_a - v_b)^2$$

$$28. \quad \epsilon_a = \epsilon_a (\rho_a, T_a)$$

$$29. \quad \hat{\epsilon}_a = \sum_b h_b (T_b - T_a)$$

Figure 8-36. Summary of Mixture Relations for a One-Dimensional, Multiphase Flow Model (Continued)

I. DEFINITIONS

1. ρ_1 = GAS DENSITY
2. ρ_2 = SOLIDS DENSITY
3. $\bar{\rho}_1$ = IN-MIXTURE GAS DENSITY
4. $\bar{\rho}_2$ = IN-MIXTURE SOLIDS DENSITY
5. ϕ = SOLIDS VOLUME FRACTION
6. $\bar{\rho}_2 = \phi \rho_2$
7. $\bar{\rho}_1 = (1-\phi)\rho_1$
8. v_1 = GAS VELOCITY
9. v_2 = SOLIDS VELOCITY
10. $G_1 = \rho_1 (1-\phi)v_1$
11. $G_2 = \rho_2 \phi v_2$

II. BALANCE EQUATIONS

CONSERVATION OF MASS (STEADY FLOW)

$$12. \frac{\partial}{\partial z} G_1 = 0$$

$$13. \frac{\partial}{\partial z} G_2 = 0$$

Figure 8-37. Solids Transport Model Equations Simplified from the Equations in Figure 8-36

CONSERVATION OF MOMENTUM (STEADY FLOW)

$$14. \quad \frac{\partial}{\partial z} (G_1 v_1 + G_2 v_2 + P_1) = F + \rho g$$

$$15. \quad \frac{\partial}{\partial z} G_2 v_2 = F_2 + (\rho_2 - \rho_1) \phi g + \hat{p}_2$$

CONSERVATION OF ENERGY (TRANSIENT)

$$16. \quad \frac{\partial}{\partial t} (\bar{\rho}_1 \epsilon_1 + \bar{\rho}_2 \epsilon_2) + \frac{\partial}{\partial z} (G_1 \epsilon_1 + G_2 \epsilon_2) + P_1 \frac{\partial}{\partial z} v_1 \\ = F_1 v_1 + F_2 v_2 + \hat{p}_2 (v_1 - v_2) + Q_1 + Q_2$$

III. CONSTITUTIVE EQUATIONS

$$17. \quad P_1 = \rho_1 RT$$

$$18. \quad F_1 = \frac{1}{2} \frac{f^1}{D} (Re_1) \bar{\rho}_1 v_1^2$$

$$19. \quad F_2 = \frac{1}{2} \frac{f^1}{D} (Re_2) \bar{\rho}_2 v_1^2$$

$$20. \quad \hat{p}_2 = \frac{1}{2} \frac{\delta}{d} C_D (Re_1, Re_2) \rho_1 (v_1 - v_2)^2$$

$$21. \quad Q_1 = h_1 \Delta T$$

$$22. \quad Q_2 = h_2 \Delta T$$

Figure 8-37. Solids Transport Model Equations Simplified from the Equations in Figure 8-36 (Continued)

I. DEFINITIONS

1. ρ_1 = WATER VAPOR DENSITY
2. ρ_2 = WATER DROPLETS DENSITY
3. ϕ = VOLUME FRACTION LIQUID
4. $\bar{\rho}_1 = \rho_1 (1-\phi)$ = IN-MIXTURE VAPOR DENSITY
5. $\bar{\rho}_2 = \rho_2 \phi$ = IN-MIXTURE LIQUID DENSITY
6. v_1 = VELOCITY OF VAPOR
7. v_2 = VELOCITY OF LIQUID
8. $G_1 = \bar{\rho}_1 v_1$
9. $G_2 = \bar{\rho}_2 v_2$
10. P_1 = SATURATED VAPOR PRESSURE
11. F_1 = GAS FRICTIONAL PRESSURE DROP
12. F_2 = LIQUID FRICTIONAL PRESSURE DROP
13. $\hat{c}_1$ = MASS SUPPLY TO VAPOR PHASE
14. $\hat{p}_2$ = DIFFUSION FORCE ON LIQUID PHASE
15. g = GRAVITY FORCE
16. $\rho = \bar{\rho}_1 + \bar{\rho}_2$ = MIXTURE DENSITY

Figure 8-38. Relations for a Two-Phase Model with Phase Change

II. BALANCE EQUATIONS

CONSERVATION OF MASS (STEADY FLOW)

$$17. \frac{\partial}{\partial z} G_1 = \hat{c}_1$$

$$18. \frac{\partial}{\partial z} G_2 = -\hat{c}_1$$

CONSERVATION OF MOMENTUM (STEADY FLOW)

$$19. \frac{\partial}{\partial z} (G_1 v_1 + G_2 v_2 + P_1) = F_1 + F_2 + \rho g$$

$$20. \frac{\partial}{\partial z} (G_2 v_2) = F_2 + (\rho_2 - \rho_1) \phi g - \hat{p}_2 = \hat{c}_1 v_2$$

CONSERVATION OF ENERGY (TRANSIENT)

$$\begin{aligned} 21. \quad & \bar{\rho}_1 \frac{\partial}{\partial t} \epsilon_1 + \bar{\rho}_2 \frac{\partial}{\partial t} \epsilon_2 + \frac{\partial}{\partial z} (G_1 \epsilon_1 + G_2 \epsilon_2) + P_1 \frac{\partial}{\partial z} v_1 \\ & = F_1 v_1 + F_2 v_2 + \hat{p}_2 (v_1 - v_2) - 1/2 \hat{c}_1 (v_1 - v_2)^2 \\ & + Q_1 + Q_2 \end{aligned}$$

III. CONSTITUTIVE EQUATIONS

$$22. P_1 = P_1(T)$$

$$23. F_1 = 1/2 \frac{f^1}{D} (Re_1) \rho_1 v_1^2$$

$$24. F_2 = 1/2 \frac{f^1}{D} (Re_2) \rho_2 v_2^2$$

$$25. \hat{p}_2 = 1/2 \frac{\delta}{d} C_D (Re_1, Re_2) \rho_1 (v_1 - v_2)^2$$

$$26. \hat{c}_1 = \hat{c}(T, v_1, v_2, \frac{\partial}{\partial z} T, \frac{\partial}{\partial z} v_1, \frac{\partial}{\partial z} v_2)$$

$$27. Q_1 = h_1 \Delta T$$

$$28. Q_2 = h_2 \Delta T$$

Figure 8-38. Relations for a Two-Phase Model with Phase Change (Continued)

Figure 8-39. Mass Flow Rate Densities of a Two-Phase Flow, Water-Steam Mixture

Figure 8-40. Flowing Steam Temperature of a Two-Phase Flow, Water-Steam Mixture

Figure 8-41. Flowing Steam Pressures of a Two-Phase Flow, Water-Steam Mixture

Figure 8-42. Flowing Stream Velocity of a Two-Phase Flow, Water-Steam Mixture

for computer simulation and presentation in an article. Also, the formulation of the contents of each article has begun.

An article entitled "Predicting Accurate Downhole Temperatures Improves Well Designs" will serve as an introduction to the series, describe the computer model to be used, and present some results on sensitivity to flow variables.

Industry involvement will be solicited, example calculations selected, and the contents of each article defined during the first 6 months of the task. It is planned that the first article can be reviewed by all parties and submitted to World Oil in July 1981. Subsequent articles will be submitted one per month, with the last article presented in December 1981.

References

¹R. R. Angel, "Volume Requirements For Air or Gas Drilling," Transactions, Volume 210 (AIME, 1957) p 325.

²K. E. Gray, "The Cutting Carrying Capacity of Air at Pressures Above Atmospheric," AIME Paper No. 874-G, Dallas, Texas, October 1957.

³Carl Gatlin, Petroleum Engineering, Drilling and Well Completions, (Englewood Cliffs: Prentice-Hall, Inc., 1960).

⁴J. H. Keenan et al, Steam Tables, (New York: John Wiley and Sons, 1969).

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>CASING STRESS ANALYSIS</u> CASING THERMAL STRESS STUDIES													

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

8.6 Casing Stress Analysis

Sandia National Laboratories
Technical Consultant: C. M. Stone (505) 844-5113

Project Objective

The objective of this project is to demonstrate that existing analytical techniques for thermal stress analysis can be applied to geothermal casing applications. Finite element analysis using existing state-of-the-art techniques will be applied to generic geothermal casing problems. Results from these studies will demonstrate how the analytical techniques can impact well completion.

Project Status

Several geothermal casing problems have been identified for study using the analytical techniques. One of these casing studies has been completed. The stress distribution in a tie-back liner and the surrounding casing/cement has been determined for the conditions of well completion and shut-in.

Quarterly Progress

A thermal stress analysis of a multiple casing string/cement configuration was performed, and the stress distribution in the casing/cement was determined. The physical problem of interest is shown in Figure 8-43. A

Figure 8-43. Casing Configuration Used in the Analysis

thin section of casing/cement was subjected to an exponential rise in surface temperature and pressure which simulated the physical process of cementing a tie-back liner to the surface and then closing the well. Closing the well caused the temperature in the wellbore to rise. A multiple step analytical process was required to determine the stress distribution in the casing/cement.

The first step in the process was an accurate assessment of the temperature distribution in the casing/cement section. The computer program GEOTEMP was used to define the stress-free temperature distribution in the section after the tie-back liner was cemented in place. GEOTEMP used actual well completion data in order to provide an accurate estimate of the temperature distribution. It was assumed that the borehole temperature increased in an exponential manner from the initial value 25°C (77°F) to a final value of 238°C (460°F) four hours after the well was shut-in. The internal pressure was also assumed to rise in a similar exponential manner from 0 to 3103 kPa (0 to 450 psi) in four hours. Using the stress-free temperature distribution as initial conditions, a transient thermal conduction analysis was performed using COYOTE, a finite element thermal code. The analysis assumed that the wellbore temperature varied exponentially with time. The results of the transient analysis are shown in Figure 8-44. The curves shown are at 4-hour intervals after shut-in.

The computed transient thermal solution is used in the second step of the analytical process, the structural solution. Temperature difference between the stress-free temperature distribution and the transient temperature distribution act to deform the casing/cement system. The structural boundary conditions are shown in Figure 8-45. In addition to the time-varying borehole pressure, an external constant pressure is applied to simulate the effect of geostatic pressure. An additional consideration is the inclusion of initial stresses due to the hanging weight of the individual casing strings. These weights are also corrected for the buoyancy effect produced by the flowing mud and cement. Initial hydrostatic stresses are also assumed to exist in the cement due to the weight of the cement above the section. An incremental elastic analysis was performed using MARC, a finite element structural code, and included all of the effects previously cited. The results of the analysis showed that yielding will occur in the 24.5-cm (9-5/8-in.) casing string. Also, the presence of large compressive stresses in the cement between the 24.5-cm and 34.0-cm (9-5/8-in. and 13-3/8-in.) casing strings indicates that crushing of the cement would probably occur. These results do not represent failure of the casing or cement but indicate the structure is altered significantly from its original state and that these changes should be considered in other analyses and well assessments.

Future work will expand on this model to incorporate cyclic periods of production followed by shut-in.

Figure 8-44. Transient Temperature Profiles Computed by COYOTE

P_i - PRESSURE PRODUCED INSIDE CASING

P_o - EXISTING OVERBURDEN PRESSURES

Figure 8-45. Boundary Conditions for Structural Analysis

9. ADVANCED DRILLING SYSTEMS

Advanced and innovative drilling systems will be required in order to meet long-term well cost reduction goals. The approach to the development of advanced systems involves investigations of high-pressure water-jet erosion drilling systems, cavitating jets, improved downhole motors, high-speed bits, and percussion drills. The investigations include laboratory testing and field demonstration of full-scale devices. Projects are presently under way to (1) improve downhole motor bearings and seals, (2) evaluate the potential of percussion drilling devices for use in the geothermal environment, (3) optimize the design of cavitating-jet nozzles for use with rock cutting bits, (4) develop high-pressure fluid delivery systems compatible with fluid-jet drill bits and downhole motors, (5) demonstrate that high-temperature/high-pressure polymers are compatible with flexible drilling pipe, and (6) evaluate the performance of PDC bit designs at high speeds. The objectives of these projects are to develop and demonstrate hardware incorporating these concepts so that increased rates of penetration and longer downhole drilling periods may be achieved. The projects to design, fabricate, and demonstrate a water-jet erosion drilling underreamer and to design, fabricate, and laboratory test a pressure-pulsing device for use with cavitating jets were completed in FY80. The status and progress of the on-going activities are described within this section.

A field test of a hybrid, high-pressure-water-jet/roller-cone bit has been completed. The test demonstrated that the optimum penetration rate in dolomite was achieved with a 1.8-mm (0.07-in.) nozzle at 96.5 MPa (14,000 psi). Also, penetration rate improvements as a function of the water-jet direction ranged from 200% with an axial direction to 700% at a bit-gage direction. These improvements were recorded after a threshold pressure of 82.7 MPa (12,000 psi) had been reached. The final report on the field test is in preparation.

The experiments to establish a standard for testing rock resistance to cavitation attack have been completed. Samples of granite, marble, sandstone, and dolomite were subjected to cavitation attack, and the mean and cumulative depths of erosion over a 7-hour period were recorded. The data were used to correlate rock response to cavitation/water-jet action.

Laboratory tests were completed to establish the design parameters for a cavitating-type jet nozzle using drilling mud as an erosion medium. The experimental program established the feasibility of utilizing cavitating jets to drill deep holes for geothermal and petroleum extraction. The results indicated that cavities can be formed under high ambient pressures. Once formed, these cavities have a rock damage potential that increases as the third power of borehole pressure, and the rock cutting rates increase

approximately as the third power of nozzle pressure drop. It was further shown that the use of drilling mud imposes no adverse effects upon jet performance. These results led to the conclusion that cavitating jets may be used in conjunction with mechanical bits to drill deep holes at increased penetration rates with existing rigs and hydraulic equipment. A follow-on project to optimize cavitating-jet nozzle design is under way.

A facility for testing downhole motor bearing and seal packages under simulated downhole conditions has been completed. The facility permits the testing of candidate bearing/seal packages with full-scale motors at simulated downhole conditions of 300°C (572°F) and 34.5 MPa (5,000 psi). The design parameters include a differential pressure across the bearing/seal package of 0 to 13.8 MPa (0 to 2,000 psi), a flow rate of 0.006 to 0.013 m³/s (100 to 200 gal/min), a rotational speed of 100 to 1,000 rpm, and a dynamic load to 267,000 kN (60,000 lb). The facility is currently in use in the project to improve downhole motor bearings and seals.

The performance potential and economics of erosion drilling systems were assessed and characterized. These activities involved the collection, analysis, and presentation of the available data. The final report on the project is nearing completion.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>STUDY OF HIGH-PRESSURE JET DRILLING TECHNOLOGY: FOSTER-MILLER</u> STATE-OF-THE-ART ASSESSMENT ESTABLISH SYSTEMS DEFINITION AND COSTS ESTABLISH SYSTEMS OPERATING CHARACTERISTICS AND REQUIREMENTS EVALUATE OPERATIONAL IMPACTS RECOMMEND NEEDED DEVELOPMENT FINAL REPORT													

LEGEND: ————— ACTIVITY PERIOD ○ PLANNED START ▽ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▼ COMPLETED

9.1 Characterization of High-Pressure Jet Drilling Systems

Contractor: Foster-Miller Associates, Inc. (FMA)
Principal Investigator: A. Guzdar (617) 890-3200
Contract Period: 1 August 1979 to 28 February 1981
Contract Number: 13-8728 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

Project Objective

Sandia personnel are conducting a study to assess the performance potential and economics of erosion drilling systems for geothermal resource recovery. Data characterizing the performance of erosion drilling systems investigated in the past are needed as input to this study. The objective of this project is to gather, analyze, and present these data. In particular, this project will supply data for the various systems relating to

1. System hardware requirements and costs,
2. Penetration rates,
3. Bit lifetime,
4. Operating and rig costs,
5. Downtime,
6. Maintenance requirements,
7. Operational characteristics,
8. Time requirements for necessary operations, and
9. Impacts on other drilling and completion operations.

In addition, areas of potential system improvements and increased efficiency, required technology and hardware development, and additional analytical, experimental, and field work requirements will be identified.

Project Status

Project activities were initiated in August 1979. The state-of-the-art assessment was completed. Coordination was made to assure a proper interface between the study output and the Sandia Well Cost Simulation Model. An erosion drilling information computer search was made. Detailed data were obtained from company files on the high-pressure projects conducted by Gulf Oil Company and Exxon Production Research. Some data were obtained from Shell Research on their high-pressure experience, and they reported that most of their data were available in public literature. A request was made to Hughes Tool Company, but they declined to make available their company data on high-pressure drilling. The assessment of all available data was completed, and system cost estimates based on the data were made.

The final economic analysis was completed. Typical East Mesa geothermal well costs were received. The final report is nearing completion. A no-cost time extension to 28 February 1981 was granted. An additional extension is being considered so that FMA can modify the final report as requested by Exxon.

Quarterly Progress

Gulf and Exxon reviewed the final report this quarter, and Exxon requested that changes be made. Exxon also requested that the economic analysis be redone to provide a more realistic comparison with conventional drilling. A revision of the analysis would require additional funding and another extension of the contract period. Gulf has yet to respond. A determination of the actions to be taken to complete the project was in progress as the quarterly reporting period ended.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>DOWNHOLE MOTOR SEALS AND BEARINGS; TERRA TEK</u>													
SEAL TESTING													NOV 81
BEARING/SEAL PACKAGE TESTING													NOV 81

LEGEND: ACTIVITY PERIOD
 RESCHEDULED

 PLANNED START
 STARTED

 PLANNED COMPLETION
 COMPLETED

9.2 Improvement of Downhole Drilling-Motor Bearings and Seals

Contractor: Terra Tek, Inc.
Principal Investigator: P. DeLaFosse (801) 584-2400
Contract Period: 1 November 1980 to 30 November 1981
Contract Number: 74-6607 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The application of downhole motors to geothermal drilling has been limited because of short bearing and seal life in the high-temperature geothermal environment. The specific objective of this project is the development of a 200-hour-life bearing and seal package adaptable to most types of downhole motors that can soak at 260°C (500°F) and operate at a 121°C (250°F) circulation temperature.

Project Status

Under previous contracts, (1) facilities were developed to test seals and bearing/seal packages at geothermal downhole conditions up to 300°C (572°F) and 34.5 MPa (5,000 psi), (2) selected standard seals were tested to determine baseline performance, (3) new seals designed in cooperation with the seal industry were tested in the laboratory, and (4) a bearing/seal package for downhole motors was designed and laboratory tested in the Bearing/Seal Package Test Facility.

A new contract was issued last quarter to continue the bearing/seal package work. Both the seal tester and the Bearing/Seal Package Test Facility were overhauled in preparation for the next series of tests. Seal and bearing testing and evaluation continued this quarter.

Quarterly Progress

A planning and review meeting was held at Terra Tek, Inc., in Salt Lake City, Utah, near the end of the last reporting period. Test results gathered and procedures established since the previous review meeting were examined, and the test plans for the current phase of seal testing and evaluation were established.

A project review was also presented to the Geothermal Drilling and Completion Advisory Panel in Albuquerque on 20 January 1981.

Phase IV Final Report — The Phase IV Final Report on the project was completed and distributed early in this quarter.¹ The conclusions from that report follow.

1. The shaft/seal combination must be considered together in establishing a solution for the sealing problem. The two components of the problem may not be separated.

2. Repeatable tests in the seal test machine have been demonstrated for the HTCR SF-design seal (Figure 9-1).

Figure 9-1. HTCR SF-Design Seal Cross Section

3. Sintered graphite appears to be too brittle to be used as a material for the seal adapters.
4. The 1.27-cm (1/2-in.) cross section canted seal (Figure 9-2) does not provide enough flexibility to prevent damage during installation of the individual seal rings. Further testing of the canted seal should be performed with the 1.9-cm (3/4-in.) cross section seal which can be installed as a cartridge unit.

Figure 9-2. Canted Seal Cross Section

5. The Variseal® (Figure 9-3) is a viable candidate seal if long test repeatability can be established. Through three tests, this has not been done.

Figure 9-3. Variseal® Cross Section

Seal Testing and Evaluation -- Four seal tests were completed during this reporting period, (see Table 9-1). Following is a description of each test.

Table 9-1
Seal Test Conditions

Test No.	Seal Type	No. of Pressure Rings	Duration h	Shaft Coating	Diametrical Clearance: Shaft to Backup Rings		Mud
					mm	(in.)	
054	HTCR SF design	2	16.7	Carburized steel	0.127	(0.005)	No
054A	HTCR SF design	2	9.2	Carburized steel	0.127	(0.005)	No
054B	HTCR SF design	3	1.0 (Aborted)	Carburized steel	0.127	(0.005)	No
054C	HTCR SF design	1	7.8	Carburized steel	0.127	(0.005)	No
055	HTCR SF design	2	In progress	Carburized steel	0.127	(0.005)	No

Note: All tests were run at 412 rpm and at a ΔP of 10.3 MPa (1,500 psi).

DMT-054 was run with a stack of two HTCR SF-design seals, a carburized steel sleeve, and a backup ring having a tighter diametrical clearance of 0.127 mm (0.005 in.). The test ran for 16.7 hours before the lower seal had leaked 1 gallon of lubricant, and the test was terminated. A posttest inspection of the seals, adapters, and spacers showed that the male and

female adapters of the lower seal pack and the male adapter of the upper seal pack had spun during the test causing the seal rings to deform. The seal test machine was modified with dowel pins through the lower nut, spacers, and adapters to prevent rotation.

DMT-054A was run with a stack of two HTCR SF-design seals, a carburized steel sleeve, a backup ring having a tighter diametrical clearance of 0.127 mm (0.005 in.), and the female adapter of the lower seal pack pinned to the lower nut. The test ran for 9.2 hours before the lower seal pack had leaked 1 gallon of lubricant. A posttest inspection showed that the seals in the lower seal pack had spun but that the adapters and spacers had not spun. Also, the lower seal pack had not leaked until the seals had started spinning. These results were communicated to Utex Industries. Utex recommended that DMT-055 be run with a stack of three HTCR SF-design seals.

DMT-054B and DMT-054C were run under the conditions shown in Table 9-1. DMT-054B was aborted at 1.0 hour, and DMT-054C lasted 7.8 hours. From a posttest examination of the seals and shafts tested in DMT-054 through DMT-054C, it was concluded that the premature failure of the seals was caused by inadequate lubrication.

Pacer Lubricants was informed that their PLX-014 lubricant, used in these tests, was more viscous than the Texaco EP85-90 lubricant previously used. Pacer mixed another batch of the PLX-014 lubricant, giving it the same viscosity as the EP85-90. The lower viscosity lubricant provided by Pacer was installed in the seal tester, and DMT-055 was started. This test is in progress with approximately 45 hours of running time and very little lubricant leakage. The lower viscosity lubricant apparently has solved the problem of the spinning of the seal stack.

Bearing/Seal Package Testing and Evaluation -- Tests are continuing with the Dyna-Drill bearing packs in the Bearing/Seal Package Test Facility. At the completion of these tests, the Maurer bearing/seal package will be tested.

The pump for the Bearing/Seal Package Test Facility separate mud system was received. The installation of the mud system is continuing.

Reference

- ¹G. A. Tibbitts et al, "Phase IV Final Report--Program for the Improvement of Downhole Drilling Motor Bearings and Seals," Terra Tek, Inc., Report No. TR80-88, Salt Lake City, Utah, November 1980.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ——— ACTIVITY PERIOD
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○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.3 Design and Fabrication Support of Bearing/Seal Research

Contractor: Maurer Engineering, Inc.
Principal Investigator: J. Barnwell (713) 683-8227
Contract Period: 1 January 1981 to 31 December 1981
Contract Number: 74-6679 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to provide the required design, manufacturing, test assistance, and posttest component analysis support for the development of downhole drilling-motor bearings and seals.

Project Status

Maurer Engineering has been providing support services to the bearing/seal research being conducted by Terra Tek, Inc. The required support services are continuing under this contract with Sandia. The design and manufacture of the parts necessary to install and test mechanical face seals in the bearing/seal package are under way. Test assistance and failure analysis are expected to begin during the next reporting period.

Quarterly Progress

The design and manufacture of the parts necessary to install and test two mechanical face seals in the bearing/seal package were initiated this quarter. Parts for one face seal assembly have been designed and are being fabricated. Parts for the second assembly will be designed and fabricated about June 1981.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>PERCUSSION DRILLING HAMMERS AND BITS</u>													
CONVENTIONAL PERCUSSION SYSTEMS TEST S (DRL)													
DESIGN OF IMPROVED PERCUSSION SYSTEMS													
IMPROVED PERCUSSION SYSTEMS TESTS (DRL)													
DATA COLLECTION													
BIT GAGE WEAR (CSM)													
HOT ROCK DRILLING (CSM)													
INDUSTRIAL DATA (RTI)													

LEGEND:

———— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.4 Percussion Drilling Hammers and Bits

Sandia National Laboratories
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to gather data on percussion drilling by testing conventional percussion tools, by designing and testing improved percussion tools, and by surveying existing data from industry and publications. The gathered data will support an economic analysis that can be used to evaluate percussion as a candidate advanced drilling system.

Project Status

The testing and analysis of conventional percussion drilling devices and the designing and testing of improved percussion systems have been completed. The collecting of data on bit gage wear and on hot rock drilling is continuing, as is the collecting of data from industry and from the literature.

Quarterly Progress

The data collection effort on bit gage wear and on hammer performance in high-temperature rock continued throughout this reporting period. Technical work was sustained at a low level of effort pending output from the economic analysis that will focus the technical effort on the most sensitive economic components.

Following a literature survey on experiments to quantify the gage loss in solid head percussion bits with hemispherical tungsten carbide button inserts, drilling tests were conducted at the Colorado School of Mines (CSM). These drilling experiments were carried out in two types of rock, gneiss and granite. Bit wear was measured at intervals during the drilling sequences. The same rock types and bits are being used in drilling experiments at ambient and high temperature to determine the effect of rock temperature on drilling performance.

The results of the CSM experiments will be included in the next quarterly progress report.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>IMPROVED CAVIJET®</u> <u>NOZZLES: HYDRONAUTICS</u>													
INITIAL NOZZLE TEST (DRL)	COMPLETED												
MODIFY TEST FACILITY	COMPLETED												
FLUID-DYNAMIC STUDIES	COMPLETED												
ROCK CUTTING TESTS													
FINAL NOZZLE TESTS	▽												
NOZZLE CHARACTERIZATION TESTS	●-----▽												
FLUID DYNAMIC STUDIES (UCSD)	-----▽												
INITIAL BIT TESTS (DRL)	▽												
FLOW STUDIES	●-----▽												

LEGEND:

———— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.5 Development of Improved Cavijet® Nozzles

Contractor: Hydronautics, Inc.
Principal Investigator: A. F. Conn (301) 776-7454
Contract Period: 18 February 1980 to 10 May 1981
Contract Number: 13-5129 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

Project Objective

The objective of this project is to increase the knowledge of Cavijet® nozzle design principles and to develop Cavijet® nozzles that achieve increased incipient and optimum cavitation numbers.

Project Status

The initial nozzle tests at the Drilling Research Laboratory (DRL), Salt Lake City, Utah, and the modification of the Hydronautics test facilities were completed in FY80. Rock cutting tests and cavitation inception studies are continuing. The initial bit tests at DRL have been completed.

Quarterly Progress

Cavitation Inception Studies -- The first diffuser profile, which was designed to reduce internal losses occurring during the use of the Pulser-Fed Cavijet®, was tested within the air-flow facility. This preliminary design reduced the losses from 22% to 15%. However, a slight decrease was observed in the ratio u'/u , i.e., fluctuating nozzle velocity to mean exit velocity, from about 34% without the diffuser to about 27% with this preliminary insert. Work on reducing these internal losses is continuing.

Initial Bit Tests at DRL -- The bit tests were completed at DRL at the close of the last reporting period. A total of 106 runs was made on the six specimens of Mancos shale used with three NL/Hycalog Stratapax™ bits for this series of tests. The bits were essentially the same except that one bit had three plain Cavijet® nozzles installed in its matrix, one had three Pulser Cavijet® nozzles, and one had three Hughes Tool Company nozzles. A preliminary analysis of the data indicated the following:

1. The three-bladed, 21.6-cm (8-1/2-in.) diameter Stratapax™ bit design is relatively insensitive to hydraulic horsepower and pressure drop across the nozzles. This result was not anticipated, and according to NL/Hycalog, it was a performance response that had not been observed before for such bits.
2. The rates of penetration for the Stratapax™ bits in drilling Mancos shale were much faster than those observed by DRL in comparable testing performed previously with a 20-cm (7-7/8-in.) three-cone roller bit.

3. "Bit break-in", i.e., slight erosion of the tool matrix to allow full design penetration of the Stratapax™ cutters, was a strong factor in these tests. In fact, linear correlations between cutter penetration and total distance drilled by each bit showed that until completed, the break-in effect outweighed all other operating parameters for a given bit weight.

Advanced Drill Bit Tests at DRL — As part of the preparation for full-scale bit tests at DRL and possibly for field trials, a test series was initiated with a 31-cm (12-1/4-in.) three-cone roller bit supplied by the Smith Tool Company. These tests, which are being run within Hydro-nautics' air-flow facility, are examining the possible adaptation of various self-resonating and "cross-driven-resonating" Cavijet® concepts. The problem to be overcome with three-cone bits is the relatively small space available for extended nozzles as compared to the space available on two-cone bits used in the earlier and ongoing Cavijet® work at DRL and in the field.

In initial tests, first with the Smith nozzles and then with plain Cavijet® and Pulser Cavijet® nozzles, substantial differences were observed in the intensity of the velocity fluctuations that these nozzles produced when in place in the Smith three-cone roller bit. At certain jet velocities, well-defined resonances were seen with the plain Cavijet® nozzles alone; these resonances were not seen with the Smith nozzles. When a self-exciting Pulser Cavijet® was placed in one position, the plain Cavijet® in an adjacent arm responded with a strong sympathetic resonance. This effect supports the concept that this phenomenon can be developed within the limited spaces of such three-cone bits. Additional efforts are being made to examine other cross-resonating Cavijet® designs and to study the placement of these "exciting" nozzles in a central-nozzle location on this bit.

In continuing the previously reported air-flow facility tests with the 31-cm (12-1/4-in.) three-cone roller bit, further runs are being made to assist in the preparations for the DRL and/or field testing. As part of this effort, the bit on hand was modified to accept a center nozzle, which is optional on this particular tool; the bit was drilled through from the pin plenum to allow a Pulser Cavijet® to be affixed in the center position. Tests are being made on this bit, using several organ-pipe configurations combined with Pulser cross-driving center nozzles.

Flow Tests in the Air-Flow Facility — Work on flow testing during this reporting period was primarily devoted to studies of pulsing concepts that are suitable for use with three-cone roller bits. As indicated previously, this effort is devoted to evaluation of the various types of resonating Cavijet® concepts to determine which nozzles would be most suitable for use within existing or moderately modified roller bit designs.

The organ-pipe concept seemed to have promise in the initial testing. Hence, recent work has focused on this type of Cavijet®. An analytical model was developed that initially was rather idealized, but has proven useful in guiding the planning and interpretation of the experiments. Test parameters include variations in the lengths and diameters of each "pipe segment" as well as details of both the inlet design and the transitions

between segments. Resonant-jet modulation frequencies and amplitudes as a function of Mach number, which may then be related to nozzle pressure drop and jet velocity with mud or water, are being determined.

A concept that utilizes multiple orifices for a Pulser-Fed Cavijet® has been designed and is now being fabricated. This prototype is being constructed so that, if successful in the air-flow facility, it can then be tested with water in the high-pressure chamber. The purpose of this multiple-orifice design is to attempt to reduce the pressure losses observed when a single-orifice pulser, of a size comparable to the downstream nozzle, is used to excite the resonance.

Flow Studies in the High-Speed Channel (HSC) -- These tests were started at the end of the last reporting period. A large Cavijet® nozzle with an exit diameter of 7.0 cm (2.75 in.) and central vortex-generating vanes was installed and preliminary runs made. A problem with air entrainment at the free surface downstream from the nozzle was encountered but was alleviated by the placing of a floating panel of foamed plastic at this location. Bubbles generated at this surface, where the jet diverges sufficiently to cause mixing, tend to migrate back and then interfere with cavitation inception observations. At Reynolds numbers of about 1×10^6 , inception numbers comparable to those reported earlier in this program (see Figure 39 of Reference 2) have been seen for this large nozzle when the nozzle is operating in the HSC at a discharge velocity of about 12 m/s (40 ft/s).

The preliminary flow study tests in the HSC were completed during this reporting period. The techniques for both visual and sonic observations of the fluid dynamics of large-scale models of cavitating jets were proven to be feasible. Both still and high-speed movies were taken, providing records of individual vortex and ring cavities issuing from the nozzles as well as the central vaporous core vortical flow. Tip vortex cavities were clearly seen; their visualization for the photographic records was enhanced by means of two different-colored dye streams emitted from a pair of vanes placed inside the clear plastic nozzle body. A hydrophone plus the visual observations were used to obtain cavitation inception numbers as a function of Reynolds number, R , for several nozzle configurations. Without contraction, the pair of vanes gave an inception number of about 3.5 at $R = 10^6$.

Rock Cutting Tests in the High-Pressure Chamber -- A test series involving three Cavijet® nozzles with orifice diameters, d , of 2.6, 6.4, and 7.9 mm (0.101, 0.250, and 0.312 in.), respectively, was completed. The contraction ratio for each of these plain Cavijet® nozzles was four. Slot cutting tests were made on Indiana limestone and Berea sandstone over a range of standoff distances, X , resulting in the ratios, X/d , of 3/5. Preliminary analyses of these results suggest that rock properties have an effect on the dependence of slot depth, h , and on the primary variables of nozzle diameter, d , and standoff distance, X . Specifically, for the Indiana limestone, these preliminary data could be correlated according to the ratio, $hX^{3/2}/d^{5/2}$. However, for the Berea sandstone, the comparable data correlation was achieved with a ratio of $hX/d^{5/2}$. Further efforts, both experimental and analytical, will be made in this aspect of the scaling of the erosion of rocks by cavitating jets.

References

- ¹G. A. Tibbitts et al , "The Effects of Bit Hydraulics on Full-Scale Laboratory Drilled Shale," Society of Petroleum Engineers of AIME, Preprint No. SPE 8439, presented at the 54th Annual SPE Fall Meeting, Las Vegas, Nevada, 23-26 September 1979.
- ²A. F. Conn et al , "Evaluation of Cavijet® Cavitating Jets for Deep-Hole Rock Cutting," Hydronautics, Inc., Technical Report No. 7821-1, August 1979.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	★												END DATE
	O	N	D	J	F	M	A	M	J	J	A	S	
<u>FLEXIBLE DRILLING PIPE : L'GARDE</u> HIGH-TEMPERATURE POLYMER COMPATIBILITY EXPERIMENTS	<div></div> <div></div>												

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

9.6 Flexible Drilling Pipe

Contractor: L'Garde, Inc.
Principal Investigator: G. Friese (714) 546-4671
Contract Period: 1 July 1980 to 1 July 1981
Contract Number: 62-1247 (Sandia)
Technical Consultant: B. Caskey (505) 844-8835

Project Objective

The objective of this project is to modify existing flexible drill pipe so that it can be used in geothermal drilling applications.

Project Status

The project was begun in the latter part of FY80. Several materials have been tested at 2.07 MPa (300 psi) and 250°C (482°F) and at 68.9 MPa (10,000 psi) and 125°C (257°F). These tests showed Teflon PFA, EPDM 267, and Aflas 291 to be the most extrusion resistant of the materials tested.

An aging study that examines the chemical effect of drilling fluids on liner candidates was initiated and is continuing.

Quarterly Progress

Progress during this reporting period was at a low level because of delays in the delivery of materials for testing. Work continued (1) on the fabrication and check out of the test apparatus to be used for testing flexible drill pipe sections and (2) on the detailed design of test drill pipe sections.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ——— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.7 High-Pressure Fluid Delivery Systems

Contractor: Flow Industries, Inc.
Principal Investigator: J. Reichman (206) 622-1500
Contract Period: 13 June 1980 to 31 March 1981
Contract Number: 49-8409 (Sandia)
Technical Consultant: V. Behr (505) 846-0301

Project Objective

The objective of this project is to develop fluid delivery systems that will be compatible, in terms of pressure, with the fluid-jet drilling and downhole motor programs. Two methods of delivering the fluid at pressure to bottomhole will be investigated; one method involves pumping the fluid downhole at the required high pressure, while the other considers pumping the fluid down at moderate pressures and using a downhole intensifier to increase the pressure to the required level. When this project is completed, it should be possible to make a decision on which type of system design would function better for a field test. .

Project Status

All design phases of the project have been completed including those related to pumps, swivels, drill pipe, and downhole intensifiers. Simple economic analyses were made to indicate which system would be the best to pursue. A final report is being drafted for presentation to Sandia National Laboratories by the end of April 1981.

Quarterly Progress

During this reporting period, emphasis was placed on the design of a downhole intensifier. The design was finished near the end of the quarter, and simple economic studies were made to help guide the final selection of the system to be developed. The preparation of the draft final report was begun for presentation to Sandia in late April 1981. This project is expected to be completed in mid-May 1981. A summary of the project work will be included in the next quarterly progress report.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ——— ACTIVITY PERIOD ○ PLANNED START ▽ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▼ COMPLETED

9.8 High-Speed Polycrystalline Diamond Compact (PDC) Drill Bits

Sandia National Laboratories
Technical Consultant: E. Hoover (505) 844-7315

Project Objective

The objective of this project is to experimentally evaluate the performance of six different PDC drill bit designs at high speeds in three different types of rock. The durability of different stud materials and bonding techniques is also an important area of investigation.

Project Status

Orders were placed in June 1979 with five commercial bit manufacturers to design and fabricate two 17.1-cm (6-3/4-in.) diameter PDC drill bits for high-speed applications. In a parallel effort, two 16.5-cm (6-1/2-in.) diameter PDC bits were designed and built at Sandia. Originally, one bit of each design was to use all LS-bonded (brazed) cutters, while the second bit was to use all diffusion-bonded cutters. Because of difficulties with the diffusion-bonding process, a mixture of diffusion-bonded cutters and LS-bonded cutters was used on the second bit.

On 16 April 1980, the LS bonded Christensen drill bit was tested at the Drilling Research Laboratory (DRL) in Salt Lake City, Utah. The bit stopped penetrating after drilling 0.9 to 1.2 meters (3 to 4 feet) into Texas pink granite. A posttest analysis of the bit revealed that the bit body was badly worn in line with the outermost PDC cutter. Apparently, the natural diamonds utilized to cut the gage were not able to remove the ridge of hard rock left by the PDC cutters.

The other five high-speed PDC bit designs were tested at DRL during the periods of 5-9 January 1981 and 4-6 March 1981. These test results are summarized in this quarterly report.

Quarterly Progress

Drill Bit Design -- The five different 17.1-cm (6-3/4-in.) drill bits designed and built for Sandia by commercial bit manufacturers are pictured in Figure 9-4. The 16.5-cm (6-1/2-in.) PDC drill bit designed and fabricated at Sandia is shown in Figure 9-5. Some of the key design features of these bits are listed in Table 9-2.

The 16 April 1980 test of the Christensen bit identified a design flaw that caused the bit to fail prematurely. As shown in Figure 9-6, the outermost PDC cutter does not extend all the way out to gage. When drilling very hard rock, the cutter leaves a ridge that cannot be removed satisfactorily by the natural diamonds alone. The early discovery of this problem resulted in removal of the Christensen bit from further evaluation.

Figure 9-4. PDC Drill Bits, 17.1 cm (6-3/4 in.) in Diameter, Supplied by Bit Manufacturers. From left to right: American Coldset, Christensen, Hycalog, Smith, and Security

Figure 9-5. Sandia National Laboratories' 16.5-cm (6-1/2-in.) PDC Bit

Table 9-2

Key Design Features

<u>Source</u>	<u>Body Type</u>	<u>No. of Cutters</u>	<u>Back Rake Angle</u>
American Coldset	Matrix	35	-20°
Christensen	Matrix	21	-11°
Hycalog	Matrix	25	-20°
Security	Steel	27	-25°
Smith	Steel	26	-20°
Sandia	Steel	21	-25°

Figure 9-6. Christensen 17.1-cm (6-3/4-in.) PDC Drill Bit after Drilling 0.9 to 1.2 meters (3 to 4 feet) in Texas Pink Granite

Two complete drill bits were fabricated for each of the remaining five designs. Originally, the first bit was to use LS-bonded carbide cutters, and the second bit was to use diffusion-bonded carbide cutters. However, problems were encountered in scaling up the laboratory-based diffusion-bonding process. In order to reduce the number of diffusion-bonded carbide cutters required to complete the bits, a mixture of LS-bonded and diffusion-bonded cutters was used. On two bits, three different types of cutters were used: LS-bonded carbide, diffusion-bonded carbide, and diffusion-bonded steel. This arrangement allowed a direct comparison of the three types of cutters. The 10 drill bits are described in Table 9-3.

Table 9-3

Experimental PDC Drill Bits

Bit No.	Source	LS-Bonded Carbide Cutters	Diffusion- Bonded Carbide Cutters	Diffusion- Bonded Steel Cutters
1	American Coldset	35	--	--
2	American Coldset	35	--	--
3	NL/Hycalog	25	--	--
4	NL/Hycalog	15	10	--
5	Security	27	--	--
6	Security	9	9	9
7	Smith	26	--	--
8	Smith	10	6	10
9	Sandia	21	--	--
10	Sandia	--	--	21

Laboratory Testing in Sandstone -- With the exception of bit No. 4, all of the bits listed in Table 9-3 were shipped to DRL in Salt Lake City for testing. The diffusion-bonded cutters on bit No. 4 from Hycalog were found to be defective after being furnace brazed into the matrix bit body.

The full-scale laboratory tests were conducted under atmospheric conditions using water as the drilling fluid. The flow rate was held constant at 0.013 m³/s (200 gal/min) for all bit tests. The bits were tested in Nugget sandstone, Crab Orchard sandstone, and Sierra White granite at two rotary speeds, 100 and 500 rpm. The sandstone tests were used primarily to establish the performance characteristics of each bit as a function of weight on the bit. The granite tests were used to evaluate the wear of PDCs in very hard rock.

The drill bits numbered 1, 3, 5, and 8 in Table 9-3 were tested in the Nugget sandstone. Each bit drilled about 1.8 meters (6 feet) without any significant wear except for a slight rounding of the diamond layer at the cutting edge. The performance characteristics at 100 rpm are plotted in Figure 9-7. The torque was limited to 1,627 N·m (1,200 lbf·ft) in all tests. The performance and torque characteristics at 500 rpm are shown in Figures 9-8 and 9-9. In general, the Smith and Hycalog bits drilled more efficiently than the American Coldset and Security bits, and the penetration rates of all bits were higher at 500 rpm than at 100 rpm.

Drill bits Nos. 1, 3, 5, and 8 were tested next in the Crab Orchard sandstone along with Sandia bit No. 9. The Sandia bit was predulled by drilling about 1.5 meters (5 feet) in the Crab Orchard sandstone prior to

Figure 9-7. Performance Characteristics of Bits Nos. 1, 3, 5, and 8 at 100 rpm in Nugget Sandstone

Figure 9-8. Performance Characteristics of Bits Nos. 1, 3, 5, and 8 at 500 rpm in Nugget Sandstone

Figure 9-9. Torque Characteristics of Bits Nos. 1, 3, 5, and 8 at 500 rpm in Nugget Sandstone

any performance testing. The performance characteristics of these five bits at 100 and 500 rpm are shown in Figures 9-10 and 9-11. The torque requirements at 500 rpm are shown in Figure 9-12. A total of 1.8 meters (6 feet) was drilled by each bit. Again, none of the five bits exhibited any significant wear other than a rounding of the diamond layer and a few small, 3.2-mm (1/8-in.), random chips.

The performance of the bits at 500 rpm is consistent in both types of sandstone except for the No. 1 bit supplied by American Coldset. The poor performance of Bit No. 1 in the Crab Orchard sandstone may have been due to poor cleaning because the bit appearance was essentially unchanged. At 500 rpm, both the Smith bit and the Hycalog bit drilled the sandstone at very high penetration rates with low bit weights of 907 to 1,361 kg (2,000 to 3,000 lb) and at torques of 407 to 542 N·m (300 to 400 lbf·ft). However, the Smith and Hycalog bits also ran much more roughly at 500 rpm than the other three bit designs. This roughness showed up as large oscillations in the continuous torque readings. The oscillations had a period of about 1 Hz and a variation of 30% to 40% above and below the mean value.

Laboratory Testing in Granite -- Seven of the bits were tested in Sierra White granite to establish their wear characteristics and to compare the diffusion-bonded cutters with the LS-bonded cutters. The American Coldset bit No. 1 that had been tested in Nugget and Crab Orchard sandstones was the first bit to be tested in the Sierra White granite. The first hole was drilled at 100 rpm and 300 rpm with variable weight on the bit. A second hole was drilled at 500 rpm with a constant weight on the bit of 13,608 kg (30,000 lb). Under these conditions, the penetration rate started at 3.7 m/h (12 ft/h) and dropped gradually to less than 2.1 m/h (7 ft/h). The torque never exceeded 1.085 N·m (800 lbf·ft). After drilling approximately 1.5 meters (5 feet) in the granite, the bit developed 3.2 mm (1/8-in.) long wear flats on many cutters, and the diamond layer on one cutter had been sheared off. Very little spalling of the diamond was evident.

The second bit from American Coldset, bit No. 2, was run next. This bit was new and had sharp, unrounded PDCs. The first 0.8-meter (2.5-foot) deep hole was drilled using a rotary speed of 500 rpm and a constant rate of penetration (ROP) of 4.6 m/h (15 ft/h). The bit weight required to maintain this ROP gradually increased from 1,905 kg to 9,253 kg (4,200 lb to 20,400 lb). Correspondingly, the torque went from 271 N·m to 542 N·m (200 lbf·ft to 400 lbf·ft). Inspection of the bit revealed that two cutters had lost their diamond compacts, two had been badly spalled, and approximately 60% of the remaining cutters had wear flats that extended into the carbide support stud.

A second hole was drilled with a rotary speed of 500 rpm and 16,783 kg (37,000 lb) on the bit. The ROP gradually decreased from 2.1 m/h to 1.5 m/h (7 ft/h to 5 ft/h), while the torque increased from 1,139 N·m to 1,491 N·m (840 lbf·ft to 1,100 lbf·ft). After drilling a total of 1.5 meters (5 feet) in the granite, the bit had large wear flats, extending well into the stud material, on most cutters. No additional compacts were lost, and none were badly spalled.

Figure 9-10. Performance Characteristics of Bits Nos. 8 and 9 at 100 rpm in Crab Orchard Sandstone

Figure 9-11. Performance Characteristics of Bits Nos. 1, 3, 5, 8, and 9 at 500 rpm in Crab Orchard Sandstone

Figure 9-12. Torque Characteristics of Bits Nos. 3, 5, 8, and 9 at 500 rpm in Crab Orchard Sandstone

For the third bit run in granite, Security bit No. 6 was used. This bit incorporated all three types of cutters: diffusion-bonded steel, diffusion-bonded carbide, and LS-bonded carbide. In the process of spudding the first hole, the bit was rammed into the rock face with over 18,144 kg (40,000 lb) of force due to an instrument failure. Subsequent inspection of the bit revealed that one diffusion-bonded steel cutter was severely damaged.

The first hole was drilled with a constant bit weight of 13,608 kg (30,000 lb) and a rotary speed of 500 rpm. The ROP gradually decreased from 3.1 m/h to 1.1 m/h (10 ft/h to 3.5 ft/h), while the torque stayed relatively constant at 1,139 N·m (840 lbf·ft). The bit was inspected and found to have fairly large wear flats extending 3.2 mm (1/8 in.) into the studs on the outer 13 cutters. The inner cutters were worn only slightly.

A second hole was drilled with Security bit No. 6 at 500 rpm and 13,608 kg (30,000 lb) weight on the bit. When the penetration rate dropped to 0.9 m/h (3 ft/h), the rotary speed was decreased to 100 rpm. The bit weight was held constant at 13,608 kg (30,000 lb). As expected, the ROP dropped initially to about 0.5 m/h (1.5 ft/h). However, the ROP subsequently increased to over 1.8 m/h (6 ft/h) and then dropped off again. At 100 rpm, the torque was relatively constant at 1,898 N·m (1,400 lbf·ft). This curious phenomenon is illustrated in Figure 9-13 and is not fully understood at this time. Because of this unusual performance, the rest of the wear tests in granite were conducted at 100 rpm.

The Sandia bit, No. 9, that had been predulled in the Crab Orchard sandstone was tested at 100 rpm with variable bit weight in three successive 76.2-cm (30-in.) deep holes. The performance results from these tests are plotted in Figure 9-14. After drilling approximately 2.4 meters (8 feet) in the granite, the bit was still in good condition with wear flats extending only slightly into the stud material. One stud had rotated about 90°, but none had spalled or sheared off.

Additional Wear Tests -- During the period 4-6 March 1981, another series of wear tests was run in the Sierra White granite. The rotary speed and flow rates were held constant at 100 rpm and 0.013 m³/s (200 gal/min), respectively. The rate of penetration was held constant at 6.1 m/h (20 ft/h) by adjusting the weight on the bit. The torque required to maintain the ROP at 6.1 m/h (20 ft/h) often exceeded 4,068 N·m (3,000 lbf·ft) as the wear flats became larger and larger. In addition, the ROP and torque become extremely sensitive to small changes in the weight on the bit as the wear flats increase. For example, a 1% change in the weight on the bit was found to change the torque by as much as 20% to 30%. The wear test results are summarized in Table 9-4.

Figure 9-13. Security Bit No. 6 Test Results in Sierra White Granite at 500 and 100 rpm

Figure 9-14. Performance Characteristics of Sandia Bit No.9
at 100 rpm in Sierra White Granite

Table 9-4

Wear Test Results

Bit No.	Source	Initial Condition	Distance Drilled m (ft)	Observed Wear
5	Security	Predulled	5.5 (18.0)	Even wear with very little spalling. The worst cutters had wear flats that extended 3.2 mm (1/8 in.) into the stud material.
8	Smith	Predulled	2.7 (9.0)	Very severe wear with several fractured studs and diamond compacts. Severe spalling and wear flats on the outer cutters.
10	Sandia	New	6.9 (22.5)	A peculiar scalloped type of cutter wear was found with some wear flats extending to the rear of the stud. Spalling was not pronounced; however, two diamond compacts were fractured but were still intact on the stud.

Test Observations -- The major observations resulting from these bit tests follow:

1. In both types of sandstone, the bits ran relatively smoothly at 500 rpm with much higher penetration rates than at 100 rpm for a particular weight on the bit. The Hycalog and Smith bits performed especially well and appear to be excellent candidates for high-speed turbine applications in medium-strength rock. The Sandia bit may also be a reasonable turbine bit because of its low torque requirements.
2. In the sandstone, the -20° back rake cutters were more aggressive than the -25° back rake cutters and appeared to have no spalling problems in these formations.
3. In the harder Sierra White granite, the bits appeared to drill better at low speeds, such as at 100 rpm, rather than at 500 rpm. This observation is not supported by extensive data, but the trend was definitely observed. Also, at 500 rpm, the wear rate per foot of rock drilled was faster than at 100 rpm.
4. In general, the -25° back rake cutters performed better than the -20° back rake cutters in the granite. Spalling was rarely observed on the -25° cutters, and the wear rate was markedly slower.
5. Few differences were observed in the durability of the three different types of cutters with the exception of the steel stud on

the Security bit that failed due to an abnormally high impact loading. Both diffusion-bonded and LS-bonded cutters performed well. In granite, the carbide studs have an edge over the steel studs.

6. As the bits develop large wear flats in hard rock, the torque becomes much more sensitive to changes in the weight on the bit. Also, the torque required to achieve moderately fast penetration rates such as 6.1 m/h (20 ft/h), often exceeds 4,068 N•m (3,000 lbf•ft).

Future Work -- Many of the wear phenomena observed in hard rock are still being investigated and may require additional laboratory tests. Two bits are essentially unworn and could be used in future tests in the laboratory or in the field on turbines. The two bits are No. 3 and No. 7, supplied by Hycalog and Smith, respectively.

APPENDIX A

Publications and Presentations

PUBLICATIONS AND PRESENTATIONS

Geothermal Drilling Technology, SAND80-2543A, by E. R. Hoover, Sandia National Laboratories, to the Hot Dry Rock Geothermal Information Conference, Santa Fe, New Mexico, 28 October 1980.

Geothermal Drilling Research in the United States, SAND80-1581C, by S. G. Varnado, Sandia National Laboratories, to the Segundo Congreso Latino-Americano de Perforacion, Petroleos Mexicanos and Instituto Mexicano del Petroleo, Mexico City, Mexico, 27-31 October 1980.

Geothermal Drilling and Completion Technology Development Program Annual Progress Report, Report No. SAND80-2179, S. G. Varnado, Sandia National Laboratories, Albuquerque, New Mexico, November 1980.

Design and Testing of PDC Drilling Bits, SAND81-0173A, by E. R. Hoover, Sandia National Laboratories, to the Geothermal Drilling and Completion Technology Advisory Panel, Albuquerque, New Mexico, 19-20 January 1981.

A Wellbore Inertial Survey System, SAND81-0162A, by A. L. McFall, Sandia National Laboratories, to the Geothermal Drilling and Completion Technology Advisory Panel, Albuquerque, New Mexico, 19-20 January 1981.

Proceedings of the International Conference on Geothermal Drilling and Completion Technology, Sandia National Laboratories Report No. SAND81-0036C, co-sponsored by U.S. Department of Energy, Comision Federal de Electricidad de Mexico, and Sandia National Laboratories, Albuquerque, New Mexico, 21-23 January 1981.

Recent Developments in Geothermal Drilling Fluids, SAND80-2702C, by 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 Division of Maurer Engineering, Inc., to the First International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, 21-23 January 1981.

Geothermal Well Costs and Their Sensitivities to Changes in Drilling and Completion Operations, SAND80-1724C, by C. C. Carson and Y. T. Lin, Sandia National Laboratories, to the First International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, 21-23 January 1981.

Drill Pipe Corrosion Control Using an Inert Drilling Fluid, SAND80-1704C, by B. C. Caskey and K. S. Copass, Sandia National Laboratories, to the First International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, 21-23 January 1981.

Sandia National Laboratories' Geothermal Drilling and Completion Technology Development Program, SAND81-0321A, by James R. Kelsey, Sandia National Laboratories, to the 10th Meeting of the Centers for the Analysis of Thermal-Mechanical Energy Conversion Concepts (CATMEC)--Southeastern Massachusetts University and Terra Tek, Inc., Salt Lake City, Utah, 24-26 February 1981.

Geothermal Drilling and Completion Technology Development Program Plan,
Report No. SAND81-0380, S. G. Varnado, J. R. Kelsey, and D. L. Wesenberg,
Sandia National Laboratories, Albuquerque, New Mexico, February 1981.

A Review of the Geothermal Drilling and Completion Technology Development
Program, SAND81-0319C, by Donald L. Wesenberg, Sandia National Labora-
tories, to the Society of Petroleum Engineers Drilling Study Group,
Houston, Texas, 19 March 1981.

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